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MAY 1951

EXCHANGE OF FUNCTION AS A CAUSE OF GEYSER IRREGULARITY[1]

GEORGE D. MARLER

ABSTRACT. The complex problem of geyser behavior is admittedly far from being solved. All geysers play irregularly, and many with great irregularity. Geysers that play with great irregularity have proved puzzling to former observers. More than fifty months of seasonal observation by the author extending over a period of twelve years have demonstrated that many geysers showing great irregularity are connected subterraneously with other springs and geysers; that from time to time, there is a shift in direction of the flow of the thermal energy from one orifice to another. This shifting of the thermal energy from orifice to orifice and back again is designated as exchange of function. In support of the thesis that exchange of function is one of the causes of vacillation in geyser behavior the behavior patterns of many of the springs and geysers, are described in some detail, especially those in the Daisy and Grand Groups.

INTRODUCTION

THE popular conception of a geyser is that it is a natural mechanism which operates at regular periods. Much of the literature which discusses Old Faithful Geyser gives the reader the impression that this geyser erupts with approximately chronometric precision. A single day of observation in the geyser basins of Yellowstone National Park would reveal that neither Old Faithful, nor any geyser where consecutive intervals can be observed, plays at set periods. Irregularities in the quiet intervals of the geysers are characteristic of all. No geyser offers an exception to this rule. Many, like Old Faithful, may for several eruptions approach regularity, but, when recorded for a longer span, all show considerable fluctuation in the lengths of their quiet intervals.

In discussing irregularities in geysers, Allen and Day (1935, p. 225) state:

"Changes in geysers may be either continuous or fluctuating. Among the various characteristics of these intermittent springs that

[1] Published with permission of Edmund B. Rogers, Superintendent, Yellowstone National Park.

are subject to fluctuations, perceptible in a comparatively short space of time as well as over longer periods, none is perhaps so important from the theoretical standpoint as the time interval between eruptions. *Progressive* changes in the length of this quiet interval are intelligible, but vacillation in behavior is puzzling."
These authorities go to some length in considering possible factors which might influence this "vacillation" in geyser behavior, such as weather, gains and losses of heat, and possible variations in water supply, but by way of conclusion they state: "Regarding the whole problem of irregularities in the frequency of geyser eruptions, we are still entirely in the dark."

Since the discovery of Yellowstone's thermal areas the period of observation has been too short to have determined whether or not there is "progressive" change in any geyser's behavior. Old Faithful, the most carefully observed geyser since discovery, does not clearly indicate any progressive or directional change in periodicity; that is, whether the length of its quiet intervals might be, on the average, increasing or diminishing. During the entire period of its observation, Old Faithful, and certain other geysers which will later be indicated, have followed a somewhat definite pattern in their eruptive behavior and have not shown the vacillation, or great irregularity, which is characteristic of so many of the geysers.

It is toward this problem of vacillation in geyser behavior that the present paper is addressed. A number of years ago the realization was forced upon me that, in certain pairs of springs and geysers, changes of behavior take place in a strikingly reciprocal way. The water level in a given spring may undergo a rise, and that in a nearby spring will correspondingly recede. Or a given geyser will cease to erupt, while a neighboring spring or dormant geyser simultaneously enters upon an eruptive cycle. Once this idea was grasped and then observationally confirmed unmistakably for a single example, I recalled numerous other instances that seemed to fit the same general pattern. For these cases, likewise, observation gradually brought confirmation of reciprocal behavior; and added examples were recognized. Inasmuch as a given spring or geyser, though it may be destined to change, may perform in the same general manner for weeks, months or years before it undergoes material modification of behavior, and because

my service at the Park since 1937 has rarely included the cold season, the process of confirmation has not been rapid. But it has now become possible to record evidence for a considerable number of examples of what may be termed *exchange of function* between thermal units—hot springs or geysers—occurring in close proximity.

Intimately related to this phenomenon of reciprocal or interchanging behavior is another inseparable condition of at least equal significance. Most of the major geysers give no indication of having direct underground connections with each other. That is to say, the eruption of any particular geyser does not have an observed effect upon other major geysers. A similar implication of mutual independence applies to many of the non-erupting springs. But there are numerous exceptions in each category. In every instance thus far recognized of interchange of function between neighboring units *there is* clear evidence of their subterranean interconnection. Indeed, it appears to be only by virtue of their common accessibility to the same local supply of underground hot water that their reciprocal interchange of behavior is possible. Realization and confirmation of this condition of sub-surface intercommunication arose and proceeded simultaneously with that concerning exchange of function.

The existence of subterranean connection is essential not only to reciprocal or competitive behavior of nearby units. It also permits and explains other notable examples of opposite import wherein neighboring units act strikingly in concert. Exemplification of this is found in the simultaneous rise (or fall) of the water level in two or more nearby springs; or in the approximate or exact coincidence of the beginning of play by neighboring geysers; or in some simultaneous manifestation of aggressive action of nearby spring and geyser, such as respective overflow and eruption.

The recorded data on Yellowstone's thermal areas support the conclusion that the geysers having underground connections with other springs or geysers have shown great irregularity in their active periods; some of them have had eruptive cycles, followed by stretches of dormancy, and *vice versa*. Occasionally some have approached regularity, but none has remained essentially unchanged in the consistency of its periods. The opposite, however, cannot be asserted, for some geysers

of conspicuous irregularity are not known to have connection with other springs or geysers.

UNCERTAINTY AS TO IDENTITY AND PERFORMANCE

The desirability is obvious of supplementing the span of my own observation on changing behavior of certain springs and geysers by resort to the earlier accounts. Before discussing specific examples of competitive or reciprocal and of cooperative performance by nearby pairs or larger groups of thermal units, reference may be made to the difficulty of securing from the multifarious past record a sure and consistent understanding of certain pertinent facts. The following comments are introduced not only toward some hoped-for clarification of earlier writings but also because they are believed to bear pertinently on the present discussion.

The present sign at the Splendid Geyser states:

"At one time this was the location of one of the most interesting geysers in this basin, but in 1892 activity ceased from this orifice and a near-by, previously unnamed opening became the source of the Daisy Geyser which can rightfully be considered as the successor to the Splendid."[2]

This does not agree with earlier records. The "Guide to Yellowstone Park[3] (1890), in commenting on the Splendid, states:

"Quite unlike other geysers, the Splendid throws its stream at a sharp angle instead of vertically, which fact, when it was first discovered, caused it to be called the Comet; this designation, however, soon gave way to its present more appropriate appelation."

As now known the Splendid does not play at an angle; its eruptions are vertical. The configuration of the Splendid orifice suggests that only an essentially vertical eruption is possible. The Daisy plays at a *sharp angle*, suggesting a comet. The "Guides" prior to 1890 offer further proof that what is now the Daisy was formerly called the Comet, and later called the Splendid. These two earlier names for the Daisy have apparently become attached subsequently to the nearby units now respectively so named.

[2] Allen and Day (1935), state that the "Daisy Geyser sprang into being when its neighbor the Splendid first became dormant (1896)."

[3] Bauer (1937), quotes Phillips as saying that the Splendid "first played in about 1892 when the Daisy which, up to that time had been obscure, began playing more regularly."

Such uncertainty and ambiguity of identification—a situation by no means confined to the units of the Daisy Group—presumably must be ascribed in part to the brevity of observation, and the common lack of explicitness in the earlier records. Each newcomer to a given site, naturally seeking to correlate his observations with the reports of predecessors, did so in the light of his own impressions and interpretations. But it seems highly probable that if the scene confronting each observer at any site had remained unchanging, far greater agreement would exist among the series of reports on any given spring or geyser. However, if a given geyser at a specified locality is reported as active and is assigned a name by observer A, but proves to be dormant though another geyser is active when B visits that same locality, B is likely to assume that the geyser he sees in action is the same geyser seen in action by A, but naturally B describes it differently. If the scene has again changed when observer C comes along, he may agree with A or B or with neither. In any case, the chance for confusion or ambiguity of identity, naming and description is obvious.

In more recent years, when many competent observers have viewed the Park, some of them repeatedly, and when reasonably accurate sketches of the location and names, and reasonably realistic descriptions of individual units have been published in accumulating numbers, fewer additions to the earlier stock of errors and uncertainties have been made. Yet the old contradictions and confusions have not been adequately explained and removed.

Some of the modern accounts correctly record certain modifications in behavior of certain geysers, such as cessation, revival or noteworthy change in period of eruption. But, on the whole, these changes of behavior are presented as if, and seem to be accepted as if, they were chance, unrelated happenings—mere challenging puzzles. The challenge and the puzzlement would, by such view, greatly increase if the complete number of instances of change in function were on record—record not only as to number of individual springs and geysers involved but also as to number of changes of function back and forth for given individuals.

The early magnified impressions of great regularity in geyser behavior—still retained by many people—and the more

recent and realistic awareness of striking though unexplained irregularity still add up to confusion, as Day and Allen have so truly emphasized. It is to be hoped that clear recognition of frequent instances of subterranean interconnection and of both competitive and cooperative action by units so interconnected may help dispel some of the prior darkness as to geyser irregularity.

EXAMPLES IN EVIDENCE

One of the first instances to draw my attention to underground interconnections and periodic exchange of function was in the behavior of Beauty and Chromatic Pools, located about 150 feet apart in the Upper Basin north of the Grand Geyser. For a period of from 6 weeks to 4 months (these are the extremes noted to date), water will flow from one pool; then, with cessation and but an inch of ebbing in the first pool and a consequent inch of rise in the other pool, flow will be maintained in the latter pool for a similar period. During its periods of overflow, the temperature of water in the deeper part of the pool then flowing is increased about 15 degrees, resulting in the destruction of the algae, which re-establishes itself during each ebb stage. Two springs in the Round Spring Group show the same characteristic exchange of ebb and flow as do Beauty and Chromatic. Their periods, if at all rhythmic, have not as yet been determined.

This interchange of function among non-erupting springs of an interconnecting group throws light upon the capricious behavior manifested by some of the geysers. An excellent example, not only of geyser vacillation but also of considerable periods of dormancy, is at times strikingly afforded by the Daisy Group. This Group consists of Comet, Daisy and Splendid Geysers, Bonita and Brilliant Pools, a small unnamed geyser 40 feet south of the Splendid and two small pools also near Splendid. These units are closely spaced within an area of about 40 by 150 feet.[4]

During most of the Park's history the Daisy has been one of the more regular and popular geysers, playing at intervals of about every 1½ to 2 hours. Daisy's connections with the

[4] Two hundred feet east of Daisy and commonly regarded as belonging to the Daisy Group, are several small springs but none show underground connections with the rest of the Daisy Group.

above-named springs and geysers is made very evident by the lowering of the water level in these other vents at the time Daisy plays. They all refill simultaneously with the Daisy; the high water level being at the top of the rims of all the craters, with the exception of the unnamed geyser near Splendid. Though the water stands at the rims of the craters prior to Daisy's activity there is ordinarily no overflow from any vent except that of the Daisy. Occasionally, though infrequently, water will rise high enough in some one of the connecting vents to cause overflow there. Such overflow is small in volume, but without exception it has been sufficient to produce dormancy in the Daisy. As long as this overflow lasts the Daisy does not erupt.

During the 1938 season, hitherto inactive Bonita Pool, an algae-coated pool, not only began overflowing but erupted as well. The eruptions were of a minor character, but frequent. This condition lasted for 3 days when eruptive activity ceased, though with a steady overflow continuing. During both the eruptive and overflow stages of Bonita, Daisy was dormant. It was while Bonita was overflowing following its eruptions, that I surmised that this overflow, though small, was robbing from Daisy the energy necessary to bring about Daisy's activity. By way of experimentation I checked Bonita's overflow by depositing three shovelfuls of fragmental sinter at the point of outlet. The water level thereupon rose slightly in Bonita, perhaps half an inch, and then remained fixed without overflow. Within a matter of minutes the water was seen to be rising in the Daisy with an increasing vigor of boiling. This condition continued until the Daisy erupted, 30 minutes after the damming of Bonita. This was the first eruption of the Daisy in 4 days. Only once since then (1939) has Bonita, during the summer season, overflowed. That overflow likewise produced the above-described condition in the Daisy, and damming of Bonita again resulted in Daisy's immediate resumption of normal behavior.

The small unnamed geyser near the Splendid will erupt one or more times during some seasons, while during others no activity is observed. Its eruptions start at about the time Daisy is due to play. Its activity produces the same lowering of water level in the other pools and geysers of the Daisy Group, the Daisy included, as does an eruption of Daisy it-

self. This geyser is small, playing about 15 feet high for about 20 minutes; its height of eruption is much less than Daisy's, but the duration is five to seven times as long. It is believed that the explanation of these differences lies in the fact that because of its small vent, this unnamed geyser requires much longer to drain the water system than does the Daisy. The occasional activity of this unnamed geyser has been taking place for a long period of time, as indelibly recorded in the geyserite surrounding its orifice.

Three times during my observation the Brilliant Pool has risen high enough to overflow; the Splendid has overflowed once. On each of these occasions dormancy resulted in the Daisy; also, without exception, the checking of the overflow by a few shovelfuls of sinter resulted in Daisy's immediate response and consequent eruption.

The Daisy's extreme sensitiveness to any loss of water is demonstrated on every windy day. Former observers have noted that the intervals of the Daisy were measurably lengthened whenever a stiff breeze blew across the Daisy and the large, shallow basin that is filled during the period of overflow. These lengthened intervals were explained as being due to the "more rapid cooling of the water as a result of the increased evaporation produced by the wind." Whatever importance should properly be assigned to this interpretation, another influence unquestionably enters. Any wind across the Daisy pool sufficient to produce waves will, when the Daisy is overflowing and approaching an eruption, increase the rate of discharge. This loss of water and consequent drain of energy tends to retard the eruption. Winds have a similar effect upon the Morning Geyser.

Since 1892 (information on present sign at Splendid) the geyser now definitely named as Splendid has played infrequently. During those occasional periods of activity which have been carefully noted, there have resulted lengthened periods between eruptions for the Daisy, the interval of the Daisy lengthening to over 4 hours following Splendid instead of the usual 2 hours between Daisy's eruptions.

If the past performances of the Splendid and Daisy Geysers, as evidenced by recorded data as well as by their structural details, are useful criteria for predicting future functioning, it would seem reasonable to expect that the Splendid may

sometime assume a new role of activity with an infrequent or quiescent Daisy.

It is questionable if the unit now known as the Comet ever played any differently from its present type of activity. It has an almost constant splashing type of eruption, the water rising a few feet above the crater's rim, most of it falling back into the crater. The drainage from the Comet does not offer the slightest suggestion that there ever was a heavy discharge of water at all comparable to the discharge from the Splendid, Daisy, or "unnamed geyser." The sinter surrounding the crater of the Comet has no erosion channels. Such channels are always a part of the surface structure where there is discharge of water at all comparable in volume to that of the other eruptive units of the Daisy Group.

In addition to the Daisy Group, other related groups which definitely show functional exchange as a cause of vacillation are the Kaleidoscope Group in the Lower Basin, the Rainbow Pool and Green Spring in the Black Sand Basin, and the Grand Group in the Upper Basin.

The Grand Group will be considered in detail because the Grand is a frequent and spectacular performer, excelling Old Faithful in height and power of display. The history of the Grand indicates that its intervals have varied from a minimum of about 8 hours to a maximum of weeks. During the eight seasons I had observed the Grand prior to the 1947 season, 18 hours and 120 hours were the extremes checked for lengths of interval. The average interval for this period was 38 hours. During the 1946 season the Grand showed an increased frequency of function over any previous seasonal observations I had made. The average interval for the season was 27 hours, as against a 44-hour average for the 1942 season—the last season prior to 1946 when any observations were made. The increased activity of the Grand during the 1946 season was but a prelude to what occurred the next year. During the 1947 season the average interval for 244 consecutive eruptions was 12 hours and 5 minutes; 7 hours being the shortest interval and 16½ hours the longest. This greatly shortened interval for the Grand was also evident the next season and until the 5th of July 1948. From that date until the close of the season Grand lapsed back to about its 1946 average. During the period of frequent activity of the Grand no dif-

ference in the duration or character of its eruption was observed as compared with those of other years.

The Grand is definitely connected with a number of other geysers—the Turban, the Vent, the Triplets and the Rift.[5] All lie within a radius of 100 feet of the Grand. The literature on the Grand, Turban and Vent Geysers discourages belief that they are connected underground. However, more complete and extended observations on the part of Peale, Comstock, Allen and Day and of others who would quote these authorities, would have been convincing to all that the sympathetic relationship between these geysers can be adequately explained by one assumption only—underground connections. During eleven seasons of observation I have witnessed the complete performances of over three hundred separate eruptions of the Grand Geyser and checked several hundred others. The unfailing synchronism and sympathetic response of the Turban and Vent during and after each eruption of the Grand seems to leave no room for doubt as to there being definite and specific subterranean connections. It is believed that all the objections raised by earlier observers can be disposed of, and in any case they must be weighed as suppositions against this record of observed performance.

None of the literature on the Grand makes any allusions to possible underground connections between it and the Triplets. I suspected possible connections from the fact that an eruption of the Triplets would seem to delay the Grand. That is, if it were average, or over average time for the Grand and the Triplets played, it would always be from 2 to 3 hours following one of these eruptions before the Grand would play. The suspicion of subterranean connections was amply verified during the period when the Grand was unusually active.

That the Triplets and the Rift Geysers largely account for the greatly increased activity of the Grand during all of 1947 and until mid-season 1948 is indicated by the following observations: During the prewar years the average interval for the Triplets was about three hours. The Rift did not play oftener than once a day. Sometime during the winter of 1946-7 the Triplets and Rift ceased playing. During all of 1947 and until July 5, 1948 no eruptions occurred. Surface conditions

[5] This geyser has received no official name. I have termed it the Rift in allusion to the opening from which it plays.

were equally indicative that none took place. It was during this period of eruptive inactivity of the Triplets and the Rift that the Grand displayed itself, not only with much greater frequency, but with a regularity which made its eruptions predictable. Sometime during the night of July 4, 1948 the Triplets and the Rift became rejuvenated. From this rejuvenation, and to the close of the 1949 season, the Grand lapsed back to about the same frequency and degree of irregularity that characterized it during the 1946 season.

The Triplets and Rift are modest spouting springs during their active phases, whereas the Grand plays to a height in excess of 150 feet. In discussion with the writer some have expressed doubt as to the ability of a minor geyser to affect the functioning of a major one, it being too much like "the tail wagging the dog." Too little is yet known regarding any geyser's mechanism to give presumptive weight to such an argument. Many phenomena come into conspicuous performance by some "trigger effect" which, by itself, seems quite inconsequential. Definite examples of this are seen at Yellowstone; *e.g.*, the return of Daisy Geyser from a dormant phase to eruptivity by an extremely slight change in water level of Bonita Pool.

Further evidence of the subterranean connection between the Grand, the Triplets and the Rift is found in that during the months when the Triplets and the Rift were non-eruptive and the Grand unusually active, the Triplets would, as unfailingly as the tides, flow before the Grand played, and their craters would empty after each of Grand's eruptions. As a matter of fact, the level of the water in the craters of the Triplets served as a very good index as to the probable time of an eruption of the Grand.

That the 1947-8 period of increased activity of the Grand was largely induced by the failure of the Triplets and the Rift to erupt seems wholly reasonable; probably the water and energy finding expression through the Grand during its show of more frequent activity were dissipated at other times by the Triplets and the Rift. When the thermal energy from the Triplets and the Rift was made available for the Grand, greater frequency for it would result.

In description of the foregoing examples, emphasis has been placed on the disparity of behavior at different orifices that

are plainly interconnected underground, and thus on the ability of a given type of behavior to shift from one to another of these orifices. Nevertheless, in some of the groups already described two or more of the orifices may continually or at certain times behave alike: Note, for example, the usually synchronous rise and fall of water level in other vents of the Daisy Group than that of Daisy itself; and also the essentially identical behavior and timing of several members of the Grand Group.

It is thus necessary to recognize, among these interconnected groups, not only the reciprocal or antithetical behavior which has here been especially stressed, but also the cooperative or concerted behavior of certain members of the group. Moreover, a given pair of orifices may for a time act in concert and later perform in opposite fashions. This is seen, for example, in the like behavior, for long periods, of Bonita and Brilliant Pools, then occasional eruption of Bonita while Brilliant remains essentially quiescent.

Another type of activity among interconnected units might well be termed a chain action. This chain action finds impressive demonstration following an eruption of Morning Geyser, a member of the Fountain Group in the Lower Basin. The Morning, Fountain, and Clepsydra Geysers (the Morning and Fountain being major geysers) erupt in series, the chain action always being initiated by the Morning. A brief description follows: Morning plays powerfully for a period varying from 45 minutes to an hour. During its activity water slowly ebbs in both Fountain and Clepsydra. Approximately 3 hours following Morning's activity the Clepsydra begins playing from four vents, one of them being in a steam phase, which in its power, is comparable to that of the Black Growler. The Clepsydra plays steadily for a period varying from 3 to 6 hours. From about 6 to 8 hours following Clepsydra the Fountain erupts, its activity lasting for the same duration as the Morning's. As closely as I can determine, this eruption of the Fountain is followed about 6 to 8 hours later by another. Both the Fountain and the Clepsydra occasionally erupt independently of the Morning, but since the 1946 season when the Morning became rejuvenated after a half-century of dormancy, I have checked fifty-two eruptions of this geyser, and without exception this chain action has taken place as described above.

Two examples of interesting behavior are added to the list here discussed, at the suggestion of Dr. L. C. Graton. The massive, undulating sinter of the Turban holds the normal water level a few inches above the surrounding, gently sloping geyserite. At the base of the Turban the veneer of sinter is punctured by the slot-like orifice of the Vent, which erupts at an oblique angle pointing away from the Turban.

The Vent and Turban play in concert with the Grand, the concerted play of Turban and Vent continuing intermittently for several hours after cessation of the Grand. During this synchronized stage of the Turban's and the Vent's functioning, the Vent is ejecting a beautiful, inclined plume some 20 feet in height, while the Turban is characterized by a series of "boiling mounds." Following this joint action the Turban continues playing, with the Vent swallowing such of Turban's overflow as is within its reach. The subterranean interconnections of Turban and Vent cannot be doubted; yet at an appropriate stage in their joint eruption, Vent reverses the direction of flow in its tube.

An entirely analogous example on a smaller scale is afforded at times in the behavior of Minute Geyser and a tiny subsidiary vent at a slightly lower elevation a few feet distant. These units, close to the road just south of Norris parking area, begin eruption almost synchronously, but the smaller one subsides first and then drinks in such of Minute's later overflow as reaches it.

CONCLUSION

Since the discovery of Yellowstone's thermal wonders the geysers which have played with the least irregularity, and which during this period have followed behavior patterns essentially unchanged, are:

1. Artemisia
2. Castle
3. Great Fountain
4. Lion
5. Lone Star
6. Oblong
7. Old Faithful
8. Pink Cone
9. Sawmill
10. Riverside
11. White Dome

All of the above-named geysers, as well as smaller ones that might be appended to the list, seem to be separate and complete units. To date no certain evidence has been discovered

that they have underground connections with any other spring or geyser. On the other hand most of the geysers which have shown great irregularity give clear evidence of having subterranean connections with other springs and geysers. Some of the more prominent of the geysers in this category are:

1. Clepsydra
2. Daisy
3. Fan
4. Fountain
5. Giant
6. Giantess
7. Grand
8. Kaleidoscope
9. Morning
10. Mortar
11. Splendid

The evidence that connecting springs and geysers produce vacillation in geysers such as Giant, Giantess, and Fountain is not as clear as with the Daisy and Grand Geysers. The fact that they and the other named geysers all show vacillation, and that all have underground connections with other springs and geysers is highly suggestive, when the data on the Daisy and the Grand are taken into consideration, that exchange of function is one of the causes of their great irregularity.

More detailed and extended observation holds promise of further determinations of the effects of underground relationships on the functioning of geysers. One of the matters especially deserving further consideration is the cause of diversion of thermal energy from one branch of a channelway to another.

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MEGABRECCIA DEVELOPED DOWNSLOPE FROM LARGE FAULTS[1]

CHESTER R. LONGWELL

ABSTRACT. Extensive bodies of coarse, unassorted debris, containing individual masses of rock tens and even hundreds of feet long, lie downslope from the margins of fault-block ranges near Lake Mead, in western Arizona and southern Nevada. Probably these bodies of megabreccia represent landslides of material shed from the rising fault blocks. Similar breccias are included in some older sedimentary formations of the region. The probable tectonic significance of such megabreccias is emphasized by comparison with accumulations of coarse debris in the vicinity of Death Valley.

INTRODUCTION

SEDIMENTARY units made up of coarse, angular fragments are common throughout the Basin and Range province. Generally such deposits lie in intermont basins, although post-depositional deformation has brought some of the older units into prominent positions on the flanks of mountain ridges. The most familiar type of deposit is fanglomerate, consisting of crudely waterlaid layers or lenses interspersed with sheets of unassorted debris that are interpreted as ancient mudflows. Old consolidated waste of this type is closely matched, in all essentials, within accumulations now building up on slopes adjoining steep mountain fronts.

Another type of sedimentary breccia, containing individual blocks of phenomenal size, occurs in unassorted masses that have large thickness and lateral extent. Of several examples known to the writer, two have been studied in considerable detail. Each of these breccias clearly developed as a migrating accumulation on the downthrown block adjacent to a large fault.

OCCURRENCE WEST OF BLACK MOUNTAINS, WESTERN ARIZONA

A large remnant of megabreccia southeast of the Hoover Dam, on the Arizona side of Black Canyon of the Colorado River, is exceptionally well exposed and easy of access (fig. 1). U. S. Highway 93, between Boulder City, Nevada, and Kingman, Arizona, traverses a marginal part of the remnant in cuts with nearly vertical walls. Moreover the valleys of several

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large washes are deeply incised into and through the deposit, giving ideal exposures and revealing the relation of the breccia to underlying rock units.

The breccia is exposed in an area about six miles long from northwest to southeast, with maximum width nearly three miles (fig. 2). Along the western side of this area the breccia lies in part on Tertiary (?) lavas, in part on Miocene (?) basin deposits that are unconformable on the lavas. On the east a wide belt of younger fan debris separates the breccia outcrop

H.D.,Hoover Dam; FR.MT.,Frenchman Mountain; Br., outcrops of megabreccia

Fig. 1. Index map of locations in southern Nevada and western Arizona. Approximate outline of Lake Mead indicated by dotted lines. Rectangle southeast of Hoover Dam incloses area shown in figure 2.

from the high ridge of the Black Mountains, composed of Precambrian gneiss, schist, and granite, cut by dikes and irregular bodies of younger igneous rocks. The spatial relations of the principal units are shown in figure 2, figure 1 of plate 1, and figure 3.

Fragments that make up the breccia were derived from Precambrian bedrock—gneiss, schist, and granite like those in the Black Mountains complex, which is the one logical source of the debris. The entire mass of typical breccia consists of broken rock; there is no matrix of clay or other fine-grained products of weathering ordinarily found in slope deposits, including mudflows. Some individual fragments are hundreds of feet long; although they are minutely shattered, large bands differing in lithology remain distinct, and exposures in road cuts or in washes may be mistaken for Precambrian bedrock in place (plate 1, fig. 2). Elsewhere discrete blocks of various sizes are imbedded in a matrix made of small fragments, all of metamorphic and granitic lithology. Although in general the body of breccia, up to several hundreds of feet thick, is unassorted and wholly chaotic, in the northwestern part of the area some lenticular beds of waterlaid slope deposit intertongue with members of the typical massive breccia.

Several sharply incised stream courses reveal the base of the breccia mass in contact with silt, gypseous clay, and gravel that probably are part of the Muddy Creek formation, tentatively dated as Miocene (Stock, 1921; Longwell, 1946). In general these beds are remarkably little disturbed; but at a few localities layers of fine-grained sediment directly beneath the contact with the breccia are crumpled, and the small folds are overturned to the west. Through a thickness of many feet directly above the base, the breccia is reduced to small angular pieces; generally these are weakly cemented, but are tightly compacted. Although the Miocene (?) sediments beneath are weak, in many small canyon-like washes they stand in nearly vertical bluffs. In such favored places digging with a pick brings to view the lower surface of the breccia, which is generally nearly plane, formed on comminuted rock. Commonly this surface is smooth, and it carries striae, trending generally with the slope; these striae are particularly well developed where the underlying material is partly cemented gravel. In some respects, therefore, the breccia mass resembles a flat

thrust plate, and it might be so interpreted if it were preserved in an ancient bedrock formation, without benefit of the surface relations that are an important part of the record. The average dip of the basal contact, so far as it is exposed, ranges from three or four degrees westward to nearly horizontal. Locally, however, near the western margin of the

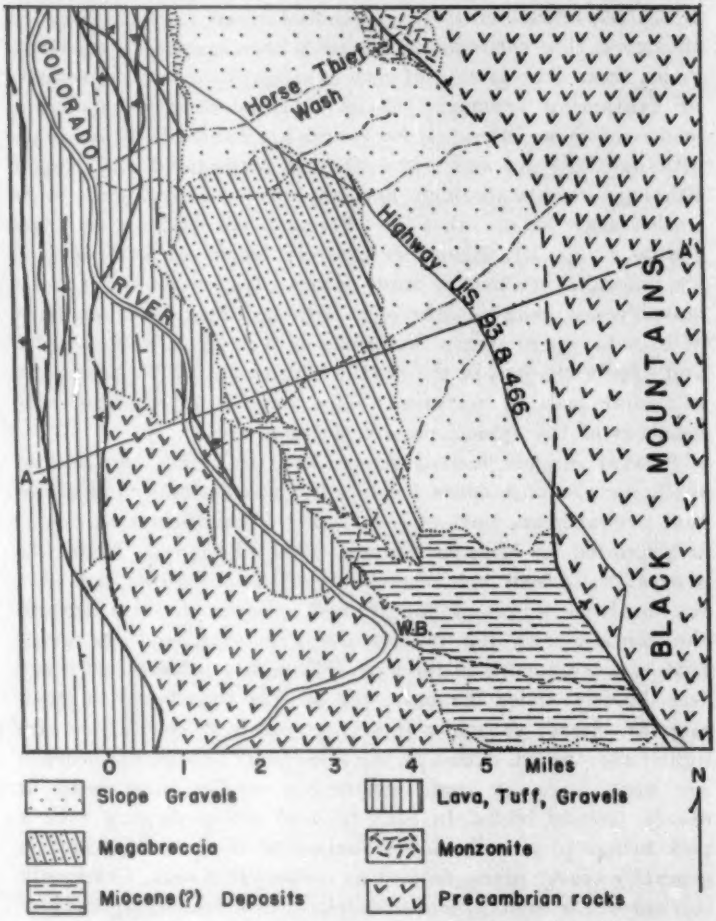

Fig. 2. Map showing geologic setting of coarse breccia west of Black Mountains. *A-A'*, line of section, figure 3. *W. B.*, Willow Beach. Dips of faults indicated by arrows.

breccia outcrop, the contact with underlying lavas is inclined eastward (fig. 3).

In the greater part of the breccia now exposed the fragments are quite fresh, and the general color tone is gray. Near the southern limit of the outcrop area, however, valleys reveal an older basal unit of the breccia that is uniformly brown from oxidation. Within this unit, component rock fragments are clearly discernible, yet many are so thoroughly weathered that they are easily crumbled by pressure of the fingers. Overlying waterlaid slope gravels, up to several tens of feet in total thickness, contain in the lower part some reworked oxidized material, and are in turn overlain by the fresh, gray breccia that is predominant in the area. Therefore two episodes of breccia development were separated by a considerable time interval. Insofar as they can be identified, fragments that make up the older unit consist entirely of metamorphic and granitic rocks like those represented in the younger unit.

The belt of fan debris east of the megabreccia has been deeply dissected by intermittent streams that are engaged in grading their courses to the profile of the Colorado River in Black Canyon. This dissection reveals that the fan deposits, as they were built up, overlapped and in part buried the older breccia, as represented in figure 3. The cross section is a composite, contsructed from evidence in a considerable area; possibly the breccia extends somewhat farther up the slope, beneath the younger debris, than the diagram indicates. However, in the southern part of the area, where the Miocene (?) basin deposits extend eastward to the base of the Black Mountains, and disappear to the north directly beneath the fan cover, breccia is present only far down the slope (fig. 2). Moreover, in the middle portion of the outcrop area the breccia

Fig. 3. Geologic section along *A-A'*, figure 2. Vertical scale same as horizontal.

mass rises to a considerably higher altitude than fan deposits exposed in large washes directly to the east (fig. 3; plate 1, fig. 1). Thus there is strong implication that the body of breccia is now separated from its presumed source, the Black Mountains block, as indicated in figure 3.

The west base of the Black Mountains in this area is marked by a zone of faulting, with upthrow of the Precambrian block on the east. Fan debris conceals the main fault in much of its trace; but in and near Horse Thief Wash there are excellent exposures of the fault surface, dipping eastward 50° to 70° between crystalline rocks in the upthrown hanging wall and strongly upturned lavas in the footwall. Miocene (?) gravels above the lavas also are tilted to a westward dip. Several miles farther south, where the highway closely parallels the straight base of the range, Miocene (?) beds are not only steeply upturned but near the Precambrian outcrops are overturned to the west, thus suggesting reverse faulting. At other localities near the base of the range eastward-dipping reverse faults that cut the crystalline rocks probably are sympathetic with the main fault hidden by fan waste. Thus cumulative evidence indicates reverse upthrow of the Black Mountains block east of the breccia outcrop.

Miocene (?) sediments accumulated in an elongate basin with high topography along the west as well as the east margin; this is established by the presence of coarse deposits along each margin, which interfinger with and grade into siltstone and gypseous clay in the middle of the basin. Presumably this was one of the numerous basins formed and maintained by faulting in southern Nevada and western Arizona during Tertiary time; the highland west of it resulted from tilting movement on normal faults, and the Black Mountains block on the east probably was a dominant topographic feature, as it is today.

The coarse breccia was derived from the Black Mountains block, as indicated by its distinctive lithology and by the small-scale but significant crumpling in the Miocene (?) basin deposits beneath. The coarse debris of Precambrian rocks is logically interpreted as a landslip mass, the front of which moved at least five miles from its bedrock source. What were the original dimensions of this mass? Clearly much of it has been removed, particularly on the south where headward ero-

sion of washes from the Willow Beach bend of the river (fig. 2, W.B) has laid bare and dissected a wide expanse of the weak Miocene (?) sediments. As indicated on the map, this dissection, with undermining action, has made the southern margin of the breccia outcrop ragged in outline. Along this thinned margin the breccia consists entirely of the extremely coarse, unassorted material that characterizes the main body of the landslip mass. Along the north margin, however, the typical breccia grades into and interfingers with much crudely bedded debris that resembles the more recent fan deposit. Indeed, it is not possible to map precisely a northern boundary of the main mass of megabreccia. Perhaps we now see the northern limit at least of one lobe of the landslip mass, although evidence that the main body extended much farther north may have been in part destroyed by erosion, in part concealed by younger fan deposits. Southward the mass may well have extended many miles beyond its present limit.

Evidence bearing on the exact cause and the detailed mechanics of the sliding is meager. Logically we may suppose that uplift of the Black Mountains fault block played an important part in setting the stage, if not in the continuing performance. Active rise of the hanging wall block would produce an oversteepened front, from which masses of bedrock might shear off under their own weight and build up an unstable slope of coarse debris. Material under such a slope might move slowly in a chronic slide, or at a time of unusual saturation by ground water it might slide catastrophically. Moreover the upthrust hanging wall may have developed conditions for instantaneous release of immense bedrock masses, to hurtle down the slope in the manner of the Frank, Alberta slide in 1903. Such a mechanism may be urged to explain the large thickness of megabreccia in its present outcrop, three or four miles from the mountain front, and its absence or much reduced thickness nearer the mountain source. Less favorable to this hypothesis, perhaps, is the interfingering of megabreccia with ordinary fan material in the northern and western parts of the outcrop area; this evidence of extensive reworking in transit seems to accord best with the concept of leisurely progress down the slope. Separation of the present breccia outcrop from the source area possibly was accomplished by headward erosion of streams that flowed into drainage basins

situated north and south of the breccia outcrop. However, the possibility that the sliding was catastrophic cannot be discarded on the basis of evidence now at hand.

Pressure exerted by the edge of the hanging wall block, in each pulse of upward movement, may have aided gravity somewhat in urging the sheet of coarse rubble downslope, though the fault is too steep for important lateral thrust. A reverse fault with low angle of dip would provide effective plunger action. Clear evidence of such action connected with the Glendale thrust, near the Muddy Valley, Nevada, is provided by the Overton fanglomerate, which includes blocks up to half a mile long, some of them samples of the thrust plate itself, others torn from the underlying bedrock and pushed by the plate onto the fan slope (Longwell, 1949, pp. 947-950). A thrust plate of this kind, moving forward on a low-angle incline, might override an extensive sheet of its own debris. Megabreccia developed under such conditions would be of mixed origin—partly sedimentary, partly tectonic.

The megabreccia west of the Black Mountains is at present dated only in relation to the basin deposits with which it is in contact. These deposits in part overlie the older, much oxidized breccia in the southern part of the outcrop area. Moreover, in at least one locality the finer basin sediments overlie as well as underlie part of the younger, gray breccia. Therefore the tentative date Miocene (?) applies to the breccia and the basin deposits alike.

The Blackhawk breccia, of the San Bernardino Mountains, California (Woodford and Harriss, 1928) is in many respects strikingly similar to the megabreccia described above. Origin of the Blackhawk breccia by landsliding from the upthrown block of a large fault is particularly convincing, since the deposit is of Pleistocene date and geomorphic evidence of its development is well preserved.

OCCURRENCE SOUTHWEST OF VIRGIN MOUNTAINS

Megabreccia extensively exposed south of Bonelli Peak, Nevada, was studied by the writer before Lake Mead was formed (Longwell, 1936, pp. 1426-28). The coarse deposit, well lithified, formed high cliffs extending several miles along the river, two to three miles from the nearest outcrops of Precambrian rocks at the margin of the range to the north-

east (fig. 1). All of the fragments in the deposit are of gneiss, schist, and granitic rocks, angular and unassorted, ranging in size from fine debris in the matrix up to blocks more than 100 feet long (plate 2, fig. 1). Some outcrops simulate exposures of Precambrian bedrock, but on close examination they are resolved into component blocks, mashed together and even intertwined, with indistinct boundaries. Crude alignment of fragments in some places suggests flowage, as in a lava mass; locally these crude "flow bands" are conspicuously bulged and contorted (plate 2, fig. 2).

The breccia is at least 400 feet thick at a maximum, and extends at least six miles parallel to the mountain front. Above it lie coarse fan deposits, the beds in which, together with the breccia mass beneath, are inclined 10° or more directly toward the source area in the Virgin Mountains block (plate 2, fig. 1). This inclination carries the breccia and the older fan deposits beneath younger fan debris near the mountain front. Presumably this relationship is the result of continued downfaulting of the piedmont block, with tilting of this block toward the fault. It is not known whether the fault is normal or reverse, since it is concealed by an apron of recent waste.

The breccia near Bonelli Peak, like that west of the Black Mountains, is interpreted as a mass of debris shed from the scarp of an active fault. This mass moved downslope until its front was at least five miles from the fault trace. The movement took place directly west as well as southwest from the Virgin Mountains block. On the west side of the Virgin River Valley and four miles north of the Colorado River, typical landslide breccia was found nearly six miles from a possible bedrock source, in contact with Muddy Creek gypseous clay. Contortion and disruption of the layers of fine-grained sediment suggest that the front of the moving mass plowed violently into playa or lake deposits on the basin floor. This genetic association with Muddy Creek sediments dates the breccia derived from the southern Virgin Mountains block as probably Miocene.

SIMILAR BRECCIAS OF EARLIER DATE

Northwest of Lake Mead, in the eastern part of the Frenchman Mountain block (fig. 1), a widespread formation made up of varied basin deposits lies with angular unconformity on

Jurassic and Triassic formations. Because of similarities both in lithology and in stratigraphic relationships, these basin deposits are correlated tentatively, but with some confidence, with Upper Cretaceous deposits in the Muddy Mountains, 35 miles to the northeast. All strata in the Frenchman Mountain block are steeply tilted, and thus the full thickness of the Cretaceous (?) basin formation, about 3000 feet, is well exposed over a wide area. At numerous horizons ranging through more than 2000 feet, masses of coarse, angular debris made up of Precambrian rock types contrast strongly with the inclosing sediments.[2] These masses vary in thickness from a few tens of feet to more than 300 feet, and range in lateral extent from a few hundred feet to more than a mile; each is a lenticular body, generally conformable to the inclosing strata which in large part consist of reddish siltstone and fine-grained sandstone, with abundant gypsum locally. Members of coarse conglomerate and of travertine-like limestone also are prominent.

The breccia in these numerous lenses is strikingly similar to that in the younger body west of the Black Mountains. Each lens consists of broken rock with essentially no matrix of weathered material. Blocks many tens of feet long are included, but most of these are extremely shattered. Many of the breccia masses afford representative assortments of gneisses, schists, and granitic rocks such as make up the Precambrian complex exposed in the Black Mountains and along Black Canyon. Several of the lenses, however, are essentially monolithologic; in at least two of large size all fragments are of gray porphyritic granite, and in others a conspicuously pink, coarse-grained granite is the only rock type. The contact surface with underlying layers of basin deposit is nearly plane and sharply defined. These layers, though they are in large part weakly cemented and consist of fine-grained material, are but slightly disturbed near the contact.

Each of the larger breccia bodies, considered alone, may suggest emplacement as a thrust plate. This hypothesis is untenable, however, because so many of the bodies, each of

[2] These breccias were recognized during a field study in 1941 by C. B. Hunt and J. H. Wiese, of the U. S. Geological Survey, and are described briefly in an unpublished manuscript by Hunt. The present writer studied and mapped the breccias in 1948-49.

PLATE 1. Megabreccia southeast of Hoover Dam

Fig. 1. View southeast across tilted lavas to hills made of megabreccia (*B-B*), more than four miles distant. Crest of Black Mountains, on skyline, about 10 miles from camera. *F*, dissected fan slope, with remnants of basalt flow at left. Black Canyon, concealed by rim, extends across view from *R* to *R'*.

Fig. 2. Typical megabreccia exposed in valley wall.

PLATE 2. Coarse breccia along river south of Virgin Mountains

Fig. 1. View downstream (northwest). Typical breccia in vertical cliffs, overlain by bedded deposits. Largest blocks in right foreground, their outlines obscured by stream erosion, are each more than 100 feet long.

Fig. 2. Detail of breccia in wall of small valley. At left, note bulge in crude alignment of fragments.

limited extent, lie at widely different stratigraphic horizons, conformable to the inclosing beds. It is here suggested that the breccia masses slid to their present positions from a high block of Precambrian bedrock that bordered the basin in which the Cretaceous (?) deposits accumulated. The nearest Precambrian outcrops at present occupy a small area at the west margin of Lake Mead, five to ten miles distant from the breccia outcrops. Possibly, however, the large thicknesses of Tertiary (?) lava that now form highlands south of the Cretaceous (?) outcrops conceal Precambrian rocks, in a block which in Cretaceous time stood high and supplied debris to the basin north of it. Wedges of coarse conglomerate that thin northward indicate clearly that a highland south of the basin furnished at least an important part of the basin fill. These recurring conglomerates, together with the bodies of megabreccia, suggest that an active fault maintained a scarp at the south margin of the basin; and that coarse rubble shed from the scarp generated a succession of landslides which moved out over the lowland, each to be buried in the growing sedimentary section.

Thick gravel deposits intercalated with Tertiary (?) lavas south of Lake Mead contain extensive units made up of megabreccia, the fragments in which were derived chiefly from metamorphic and granitic bedrock. Abundant field evidence indicates that while volcanism was active, large-scale faulting was in progress in a wide belt including the Eldorado and Black Mountains blocks. Probably, therefore, the extensive sheets of megabreccia included in the section of lavas were formed on slopes below growing fault scarps. These deposits, in scale of development and in all details of composition, are remarkably similar to the younger megabreccia exposed southeast of the Hoover Dam.

COMPARISON WITH BRECCIAS OF DEATH VALLEY REGION

Noble (1941) has described megabreccias, widely distributed and astonishingly coarse, that form prominent outcrops in an area extending eastward from Death Valley. The units made up of the largest rock fragments clearly have been involved in large-scale tectonic movements; they appear to make up extensive thrust masses, the component fragments bear the marks of vigorous movement against each other, and there is

reason to believe that thrust plates have overridden some of the chaotic assemblages of blocks. Each principal unit of *chaos* recognized by Noble has a rather distinctive lithology: in one, the Virgin Spring assemblage, the fragments were derived almost entirely from late Precambrian and lower Paleozoic sedimentary formations; the Calico assemblage consists almost exclusively of jumbled masses derived from Tertiary volcanic rocks; and the Jubilee assemblage received large contributions from granitic bedrock, although masses of Tertiary volcanic rocks and of varied sedimentary units also are important constituents.

Above the distinctive units of chaos lie thick fan accumulations known collectively as the Funeral fanglomerate, containing large members of unassorted megabreccia which Noble interprets as possible landslide masses. These masses presumably moved downslope from scarps of faults related to post-chaos folding (Noble, 1941, p. 986). However, direct evidence of these scarps has been obliterated in the eventful late Cenozoic history of crustal disturbance and erosion in the Death Valley region.

Megabreccias in the vicinity of Lake Mead are closely comparable to the breccias of the Funeral fanglomerate, not to the typical chaos. However, the relation of the breccia mass near Hoover Dam to the Black Mountains reverse fault suggests that differences between a breccia of this type and the chaos may in some circumstances be gradational. A thrust block above a fault with moderate or low inclination presumably would supply fragments of exceptional size, would aid gravity in propelling the debris downslope, and conceivably might progressively override the debris, to form a chaos sheet of large dimensions. Two or more such faults arranged in a parallel set might, by imbrication combined with normal faulting and localized erosion, produce a chaos cover with phenomenal width. Predominant lithology of the coarse debris would change as erosion of upthrust blocks might uncover successive sedimentary formations or plutonic bodies, or as thick sections of volcanic rocks might accumulate during the episode of thrusting. Landslip breccias adjacent to steeper faults would not be overridden; however, such breccia might grade laterally into typical chaos, along the strike of a reverse fault changing from high to low inclination.

Jahns and Engel (1949, 1950) have reported from the Avawatz Mountains and other parts of California breccias similar to those discussed in the present paper. As these authors note, the units they cite range in mode of origin from chiefly tectonic to chiefly sedimentary. Truly such breccias, considered as a group, are of hybrid genesis.

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YALE UNIVERSITY
NEW HAVEN, CONN.

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ORIGIN OF LIFE ON THE GALAPAGOS ISLANDS

KENNETH W. VINTON

ABSTRACT. A number of well-known scientists have held opposing views on the origin of life on the Galapagos Islands. Most of them agree that a majority of the Galapagos flora and fauna came from the same ancestral stock as the central American and West Indian species, and that the islands of the Archipelago were, at one time in the geologic past, joined into a large land mass, which allowed the present islands to be populated by a common ancestor for each race, before submergence divided the land into its present units. However, the agreement ends here and opinion differs greatly concerning the manner in which the various species arrived in this isolated habitat.

One group contends that the life forms were brought in with the flotsam and jetsam of oceanic currents, were transported by wind, or were carried by migratory birds, while the opposing group holds that the only plausible means of arrival for some of the species was by a continental land bridge.

After quoting the arguments of a number of recognized authorities on both sides of the question, the author, with some reservations, joins the flotsam-jetsam group. He proposes that a number of the strongly conflicting points on both sides of the question, for which there seems to be no logical explanation, may be solved by assuming that the submarine ridge, which now extends from Costa Rica many miles past Cocos Island, was elevated as a land bridge during Miocene time and came within a hundred miles of reaching the old Galapagan land mass. He describes the probable influence of such a bridge on the plants and animals that migrated upon it and the effect that it would have on the ocean currents, especially since the Atlantic and Pacific oceans were joined across Panama at that time. On this hypothesis a great body of conflicting, contradictory, and confusing scientific evidence concerning the manner in which the ancient Central American and West Indian flora and fauna reached the Galapagos Islands would suddenly make sense.

SINCE Charles Darwin first visited the Galapagos Archipelago in 1835, the question of the origin of the flora and fauna found there and the manner in which they arrived in that isolated spot has been a matter of vigorous academic discussion. Most of the eminent scientists who became interested in the question agree on a number of general points but divide into opposing schools of thought concerning the conditions under which the life forms reached the Archipelago.

Most scientists agree that a majority of the living things came from the same ancestral stock as the Central American and West Indian species, with some representatives from both North and South America. They also generally agree that the

islands of the Archipelago were, at one time in the geologic past, joined into a large land mass, which allowed the present islands to be populated by a common ancestor for each race before submergence divided the land into its present units. The viewpoint that most of the Galapagan life has survived through a long period of isolation is also generally approved.

However, the agreement ends at about this point, for when the scientists began debating the question of how the various species arrived in this isolated habitat, there was a great difference of opinion among them. Such authorities as Darwin, Wallace, Hooker, A. Agassiz, Slavin, Griesebach, Engler, Mortz, Wagner, Peschel, Wolf, Dall, Stewart, Stearns, Snodgrass, Heller, Robinson, Williams, McNeill, Matthews, and Townsend have expressed themselves in favor of the oceanic hypothesis, which contends that the life forms were brought in with the flotsam and jetsam of oceanic currents, were transported by wind, or were carried by migratory birds. Some in this group also think that a few of the strong flying insects may have made the long flight by their own wing power.

On the other side, serious objections and counter arguments are leveled at the oceanic hypothesis by such distinguished scientists as H. Milnes, Edwards, Murray, Baur, Hemsley, Ridgway, Robinson and Greenman, Boetger, VonIhering, Handlirsch, Scharff, Ortmann, Ratzel, Gunther, Sarasin, Gadow, Arldt, Babour, Van Danburgh, and Beebe, who favor a continental origin of the Archipelago.

One of the scientists, Robinson, changed his viewpoint in the course of his studies on the subject. In his first paper on the flora, written in collaboration with Greenman (1895), he favored the continental hypothesis but upon studying later collections he reversed his opinion and changed to the oceanic hypothesis (1902).

Dr. Stewart (1911), after spending a year in the islands making extensive botanical collections for the California Academy of Science Expedition in 1905, joined the "Flotsam and Jetsam" school when he concluded: "If these islands are continental in origin, as was maintained by Dr. Baur, one would naturally expect to find a close faunal relationship between them and the mainland, a condition, however, that does not exist. There are neither large mammals nor batrachians, both of which should be present in greater or less

quantity if the islands had been connected with the mainland within even comparatively recent geological times. Furthermore, with the exception of the large land tortoises, which are found on most of the larger islands of the group, the fauna is about what one would expect to find on almost any group of oceanic islands.

"It might be maintained that during the great volcanic disturbances that have taken place since the islands were separated from the mainland, both the mammals and batrachians were exterminated. While this might be true as far as the mammals are concerned, it would hardly be true for the batrachians, as they would very likely be able to withstand as adverse conditions as the reptiles, and it is hardly probable that a combination of circumstances would come about which would obliterate one of these groups and leave the other in a more or less flourishing condition.

"One of the strong arguments in favor of a former land connection is the presence on the islands of the well-known land tortoises, which are rather closely related to certain fossil tortoises from some of the later geological formations of North America. The presence of land tortoises on the islands is not so difficult to explain as it appears to be at first sight. While these animals are large and unable to swim, they are able to keep afloat for a considerable time, long enough to float them from the mainland to the islands if we assume that the ocean currents were as strong and had the same general trend in past geological times as they have now. The ability that these animals have of living without food for a considerable time greatly strengthens this view. During our homeward voyage from the islands, in the autumn of 1906, our live specimens of tortoises went for over a month without food, a time sufficiently long, under favorable conditions, to float an individual from the mainland of North America to the islands, if one should happen to get adrift. It would not be absolutely necessary that both male and female tortoises should be introduced on the islands to start the race, for this could be accomplished if a single female specimen containing fertilized eggs should be cast upon the shores of the islands."

Then turning to the botanical side of the question, Dr. Stewart discusses the representatives found in the eighty

families of vascular plants and makes this conclusion: "While it is no doubt true that great changes in the biological conditions must have taken place on the islands if there had been sufficient subsidence to separate them from the mainland by the depth of water that now exists, it is nevertheless not likely that the changes thus brought about would have been great enough to exterminate many families completely and to reduce all others so greatly in number of genera and species as is the case. Some genera and species would have probably become extinct if there had been a great disturbance in the biological conditions; but at the present time most families are represented by more genera on the mainland than species on the islands."

On the other hand, after studying hundreds of the large tortoises, John Van Denburgh (1914), Curator of Herpetology of the California Academy of Science, took the opposite viewpoint. He concluded that the only plausible means of arrival was by a continental land bridge. On this point he says, "Although these tortoises can live at least several days floating on the surface of the ocean, they are absolutely helpless in the water. They are unable to swim, and can only float and drift at the mercy of the winds and currents. When they drift on island shores, they usually are so battered and injured on the rocks that they only live a few days thereafter. The fact that each island, except Albemarle, has one and only one race of tortoise, is evidence that interchange of tortoises between the islands has not occurred, for such interchange would result either in preventing differentiation or in the presence of more than one race on an island.

"If the transportation of tortoises from one island to another does not occur, there is little reason to believe that tortoises, at some time in the past, have drifted over the vastly greater distance from some continent, and have reached each of the eleven islands on which they have been found, nor do we know whence they have come. The evidence offered by these tortoises, therefore, seems to be against the view that these are oceanic islands, which have been independently thrust above the surface of the water, and have received such animals as have drifted to them. We must rather adopt the view that the islands are but the remains of a larger landmass which formerly occupied this region, and was inhabited by tortoises,

probably of but one race; that the gradual partial submersion of this land separated its higher portions into various islands; and that the resulting isolation of the tortoises upon these islands has permitted their differentiation into distinct races or species."

Francis X. Williams (1911), entomologist on the California Academy of Science Expedition, in studying the butterflies and hawk-moths seemed to arrive at nearly the same conclusion as Stewart, when he says, "An island of continental origin, whose fauna has not been once obliterated by some catastrophe, would contain a comparatively large number of species, since in this case there would have been no water for the species to cross over, and barring a change of climate and a long period thereafter, the flora would remain about the same as that of the mainland from which it was separated, and at least a goodly number of the insects would persist, whereas we have seen that the insect fauna of the Galapagos is very scant. The mainland, whether we consider the Mexican, Isthmian, or South American region is undoubtedly very rich in lepidoptera, as compared with that order as represented in the Galapagos."

William Beebe visited the islands in 1923 and offers the following viewpoint (1924): "I am in perfect agreement with Van Denburgh in regard to the formation of the Galapagos by subsidence, and I go even farther and can see no explanation of the origin of the flora and fauna except through a former, direct connection with the mainland along the Central America-Panama line. But he is mistaken when he says that these tortoises are 'absolutely helpless in the water,' for we tossed the Duncan individual overboard and took hundreds of feet of moving picture film of it as it floated two miles from land. Not only did it float upright with no attempt at balancing, but considerable of the anterior part of the shell was exposed, making it possible for the head to be lowered under water, held easily clear of the surface or raised high above it.

"But the most surprising thing was the ease and excellence of its swimming ability. The reptile would swim toward the rowboat which I occupied, and finding it too high, would turn and swim over to the Noma, stretching its head high along the waterline. Then it steered its way to the companionway. This was with, across, and against the very appreciable cur-

rent at will. I could see the throat vibrate in breathing, without any detectable lowering or elevation of the body. So for a time at least these creatures have perfect control over themselves in the water."

Yet Townsend, director of the New York Aquarium, after visiting the Galapagos on several occasions and studying these large tortoises, disagrees with Beebe and Van Denburgh when he says (1925), "If a former land bridge from the American tropics, with their surpassingly rich fauna and flora, is necessary to account for the very limited number of animal and plant forms inhabiting the Galapagos, it is pertinent to inquire, Why was it so little used? Mammals are represented only by a few bats; of land birds there are only about sixty species; of reptiles only twenty-six; and of insects and of plants only a few hundreds. The transportation of some of these can be accounted for readily in other ways."

In discussing the possibility of the tortoise arriving by some means other than a land bridge, Townsend says, "The hardy tortoise, able to live for months without food or water, and like all four-legged animals, able to float and even swim for a time, would have as good a chance to survive the voyage as the lizards or any of the early involuntary Galapagan immigrants that lacked the power of flight. The ancestry of the island tortoises need not be regarded as mysterious, with so close a relative as *Testudo tabulata* living no farther away than the Isthmus of Panama. Within the past year, our associate, C. M. Breder of the Aquarium staff, has found this large and widely distributed species living in considerable numbers on the Isthmus, where it is a common pet with children of the native villages. He also brought living specimens to the Aquarium. Individuals are recorded of more than two feet in length of shell. What size and coloration it might acquire, if removed from the rainy forests of the Isthmus, where it is subject to human molestation, and placed in the dry volcanic environment of the Galapagos—this question affords food for thought. The longer we contemplate this Panama tortoise, with characteristics differing but little more from the average Galapagan animal than do the various island forms of the latter from each other, the more we are disposed to agree with Garman that "the origin of the Galapagos tortoise is directly connected with the species *Testudo tabulata* of northern South America."

With some reticence I should like to suggest a hypothesis on the origin of Galapagos life that may resolve the dilemma. Perhaps it would be wise to state the hypothesis first, then try to justify it. I emphatically object to any land connections with the Galapagos Islands since Paleozoic time, and with some major reservations join the "Flotsam-Jetsam" group. In joining this group, however, I do not propose that the ancestors of the tortoises, iguanas, snakes, flightless insects and other creatures, necessarily drifted anywhere near the 900 miles from Central America as the "Flotsam-Jetsam" group imply. Rather I would like to propose that these animals drifted from a land bridge that projected from Costa Rica through the present Cocos Island to within about one hundred miles of the ancient Galapagos land mass. This deduction will not surprise those who have studied the hydrographic charts of the Pacific coasts of Costa Rica and Panama. In the latest U. S. hydrographic charts even an amateur can see the outline of two submerged ridges or low mountain ranges that extend out into the Pacific from Costa Rica and Panama. The Panama ridge appears to have fallen a little short of reaching Malpelo Island, while the Costa Rican ridge stretches many miles past Cocos Island until it is finally severed by deep channels as it approaches the submerged Galapagos land mass. One cannot assume that the ocean bottom ever rises uniformly over a wide area, but if such an elevation did take place today and all the depths remained in their same relative position, then by the time all the islands in the Galapagos group had been rejoined into their original land mass, the Costa Rican-Cocos ridge would have risen above the sea as a low mountain range extending to within two and one half degrees of the equator. This new land bridge would fail to reach the northern fringe of the Galapagan land mass by about one hundred miles of broad shallow channels and low islands.

Hence, in subscribing to the "Flotsam-Jetsam" theory, it is with the idea that the vast oceanic distances implied in the early discussions may be reduced to a small fraction of their original values, small enough so that John Van Denburgh might have allowed the possibility of the ancestral tortoise surviving the ocean trip in a mass of tangled driftwood.

Another very important feature in connection with the

Costa Rican-Cocos bridge is that it would deflect the Panama current southwestward to deposit drifting debris on the north coast of the ancient Galapagos land as it buffered the cold Humboldt current and flowed through the wide channels separating the two lands. Furthermore, back in early Miocene time when the Atlantic and Pacific oceans were united by deep channels across the Isthmus of Panama, the strength of the Panama current must have been greatly amplified by surging waters from the Atlantic. As one stands on the Atlantic shore of Central America, braces oneself against the lashing February trade winds, and watches the mountains of blue Caribbean water that are rolled in upon the coral reefs by the north wind's steady pressure, it is much easier to imagine the tremendous volume of the Atlantic currents that must have flowed into the Pacific when no land barrier was there to stop them. During Miocene time countless numbers of huge storm-driven logs, instead of being thrown high upon the Atlantic beaches as they are today, rode into the Pacific on fast moving currents and were probably deflected southwestward toward the Galapagos Islands as the currents flowed against the Costa Rican-Cocos ridge. During those times floating objects from Costa Rica, Panama, and Colombia might very well reach the Galapagos in ten days while creatures from the lower Costa Rican-Cocos bridge might, under favorable conditions, cross the gap in less than two days. Under the best of conditions the long log trip from Venezuela or the West Indies might require from three to six weeks.

Since the oceans were connected for several million years, it would not be necessary to propose that any of the West Indian forms made the whole trip without pausing at some intermediate point for a number of generations. Furthermore, Charles Schuchert (1935), has shown that it is very probable that Panama and Costa Rica were connected to most of the West Indies by a land bridge during Oligocene and Miocene times. In this case many of the common ancestors of the present flora and fauna of both Central America and the West Indies were generally distributed in both regions, and therefore specimens from the Cocos region of the land bridge would theoretically represent the life forms from both Central American and West Indian stock.

If the submerged Cocos mountain range was raised diagon-

ally across the path of the Panama current, a vast volume of tropical water must have been directed toward the equatorial Archipelago. If we assume that this happened while the oceans were connected, it is probable that the Galapagan climate was considerably modified, for the warm Caribbean-Panama current would deflect the cold Humboldt current westward during the months of January, February, March, and April and produce a much warmer and wetter wet season than the islands now have during approximately the same months. Even today the Panama current pushing out into the broad Pacific influences the behavior of the Humboldt current to some extent and thus affects the Galapagan climate. Inversely, the climate of the Panamanian and Costa Rican coasts may have been much cooler from July to November when portions of the strong running Humboldt current may have followed this same ridge right into Panama Bay. Since there are no opposing trade winds at this season of the year, it is even possible that the cold currents may have pushed across the trans-oceanic channels and entered the Caribbean.

It might be mentioned in passing that the counter equatorial current washing the west shores of the proposed Cocos bridge could have been influential in transporting some of the Southern Californian and Mexican forms that later found their way to the Galapagos.

In referring to drifting logs in the course of this discussion, I do not mean the trimmed symmetrical types such as one sees crowded into a millpond, but great tree trunks with spreading gnarled roots, still intact, and grotesque groping arms, too large and too resistant to be crumbled by decay or torn from the parent trunk by the mechanical force of the waves. Countless thousands of these large jungle trees in Panama and Central America annually topple into nearby stream beds when the water undercuts their banks. One large tree laced with vines may pull down several lesser ones until the tangled mass of trees and vines completely block the river channel. If the stream is navigable, the natives will wield their machetes until their dugout canoe can squeeze through or under the barrier; otherwise it remains more impenetrable than the original jungle. Such tree jams become an ideal habitat for lizards, climbing snakes, tree frogs, arachnids and insects. Stream-dwelling frogs, toads, turtles, and insects

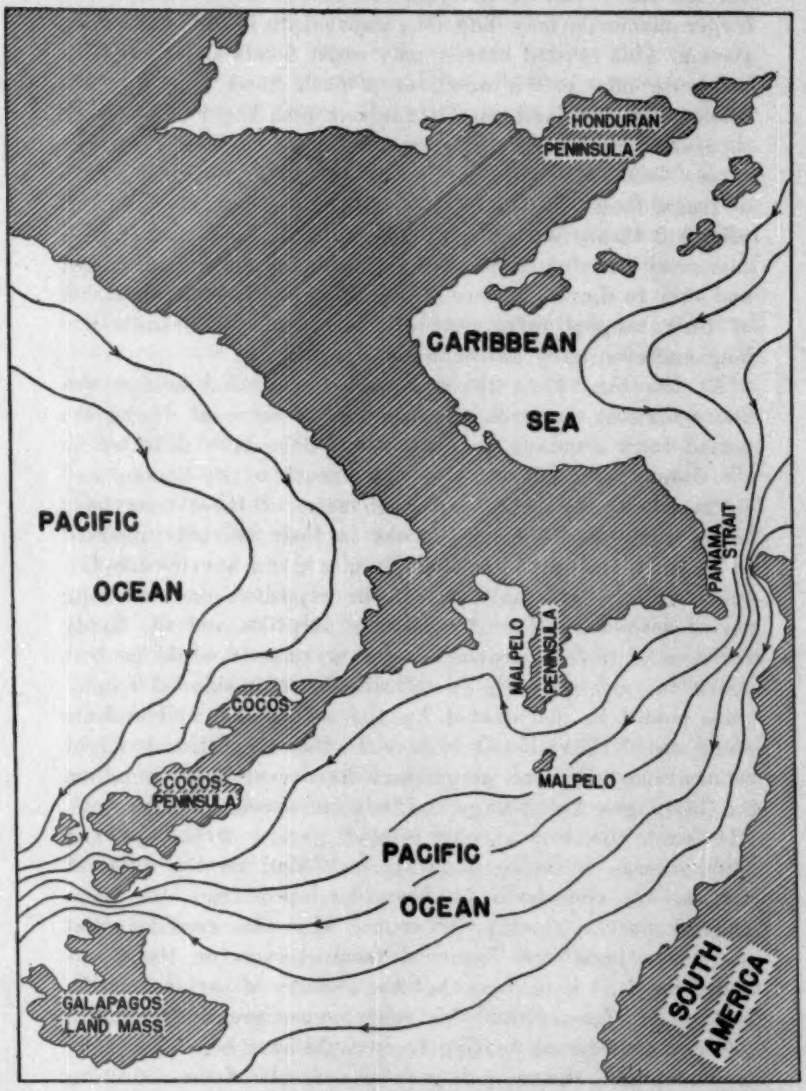

Fig. 1. Map of hypothetic Cocos peninsula and its relation to an ancient Galapagos land mass.

use the lower side of the jam for shelter while rodents and larger mammals may find it a convenient bridge across the stream. This twisted barrier may resist floods and slowly disintegrate into rotten wood, or a flash flood may tear the whole mass free and cast it far out into the Pacific. Since thousands of trees are disgorged into the Pacific by the wet season floods each year, millions of insects and large numbers of frogs, toads, lizards, snakes, turtles, and rodents undoubtedly find themselves whirling down stream on a matted tree jam every wet season. Some of them may diagnose their plight and swim to shore, but once in the safety of the upper branches of their tangled raft, most of them probably hesitate too long and eventually perish in the open sea.

At the time when the proposed Cocos land bridge was above the sea, the strong flowing Panama current during the period from January to May would have been deflected to the Galapagos landmass, depositing much of its flotsam and jetsam on those shores. Although some of these trees have hollow limbs and sheltered nooks in their twisted upturned roots, only the most tenacious species could survive the frequent wetting with salt water, the exposure, and the long period without food or fresh water. Reptiles and the hardy varieties of insects, arachnids, and myriapods would be best suited to undergo such an ordeal. The thin-skinned amphibians would be dehydrated by the salt water and rodents would die of thirst in a few days. In this connection it might be mentioned that no amphibians have ever been found on the Galapagos Archipelago and only one species of native rat. (At least the two closely related genera *Oryzomys* and *Nesoryzomys*, including four species found on the different islands, are considered to have developed from the same original parent stock.) Of course when we consider that many tree jams were launched from streams on the Cocos bridge itself, it is obvious that the chances of survival of the floating life forms from this source were greatly amplified.

Great numbers of floating trees could have been cast upon the Galapagan shores each year as a result of the deflecting action of the proposed Cocos bridge, but let us be conservative and say that the bridge caused ten Central American trees per year to be washed ashore there. Then let us continue to be conservative and say that only one tree per

thousand arrived with life upon it. In one million years, which is a brief period geologically, ten million trees would arrive and, dividing by one thousand, we have the astonishing number of ten thousand specimens. Even allowing a great amount of duplication of forms, this gives many times the number of animal species that are now living on the Galapagos Islands. After tramping over much of the barren lava-covered Galapagan sea coasts and experiencing the arid climate, one suspects strongly that the number of life forms that arrived there and perished probably exceeds the present number of living species many times over.

If there ever was a direct land connection with Central America, such as John Van Denburgh and William Beebe contend must have existed, let us repeat the question, Why was it so little used? With Central America swarming with toads and frogs, what prevented every single one of them from migrating down the bridge to the Galapagos Islands? No amphibians have ever been found on any island in the Archipelago. The author recently spent six days among the perpetually wet craters at the crest of the relatively unexplored Indefatigable Island. Scores of crater pools, marshes, ponds, brooks, and dripping lava tunnels were searched and investigated. A more ideal habitat for amphibian life would be difficult to imagine, yet not a single sign of a toad, frog, or tadpole could be found.

There is also a great horde of Central American snakes and lizards, some of which are very hardy specimens. Yet from this vast assortment, only two iguanas, one lizard, one gecko, and two closely related species of snakes reached the islands. It is difficult to see any reason why dozens of other species of lizards and snakes did not travel along the bridge with the few snakes and lizards that did reach there. Many of them are just as tenacious and would certainly have thrived just as well as the present representatives.

The Pacific coasts of Western Panama and Costa Rica are very dry at certain seasons of the year and their climate strongly resembles the Galapagan climate. Surely a great swarm of grasshoppers, crickets, beetles, ants, cockroaches and other insects would have followed the bridge down and readily adapted themselves to the changing climate. Instead, the insect population there is very scarce and scattered.

Among the native Orthoptera, for example, are found one cockroach, one mantid, eight grasshoppers, four katydids, and four crickets. Yet several species of cockroaches, accidentally imported on some of the inhabited islands, thrive abundantly. Again let us ask why so few of these hardy insects used the land bridge?

The continental bridge, if there was one, certainly must have existed before the rise of mammals, for imported rats, mice, cats, dogs, goats, pigs, donkeys, horses, and cattle run wild there today in great numbers. Had the bridge been connected after Miocene time, the rats, mice, squirrels, racoons, opposums, pumas, peccaries, deer, and other Central American mammals most certainly would have reached there. Actually the native mammals are represented by an ancient rat and a few bats. If the bridge existed during or following Miocene time, it is incredible that all of these vigorous mammals would fail to reach the islands, then fail to survive in a land where their domestic relatives flourish in a wild state today.

The Galapagan birds vary from strong-flying ducks and hawks to weak-winged warblers and fly catchers. Several of the more isolated islands have distinct species of birds. Chatham, for example, has its own species of both a fly catcher and mocking bird, while Hood Island boasts a distinct species of mocking bird. The members of the continental land bridge group might well ask how these birds arrived on the islands without a bridge, since they do not cross to the other islands, which are in plain sight of one another. In answering this question, let us remember that land connections suitable to induce these timid birds to reach the Galapagos Islands would also invite a great variety of other birds along with them. However, this apparently never happened, for the small birds there are very poorly represented. Instead, let us propose that a much stronger flying ancestor flew from island to island across a hundred miles of ocean that separated the Cocos bridge from the Galapagos land. Later submergence removed the Cocos bridge and divided the Galapagos into its segregated islands. After a long period of isolation some of the original species of birds degenerated to the point where they are unable to fly across 30 or 40 miles of water to another island. It might be mentioned at this point that the flight power of a number of Galapagan birds has degenerated

Plate 1. Tangled base of tree thrown up on Atlantic coast of Central America. Tortoises, snakes, lizards, insects or other small animals could find considerable shelter here in case a flash flood set them adrift on it.

Plate 2. The giant land iguana's overpowering urge to bite almost anything in reach, can be contained by proper handling. The author is demonstrating an effective wrestling technique on a large specimen captured in the lava rocks and cactus thickets on north Seymour Island.

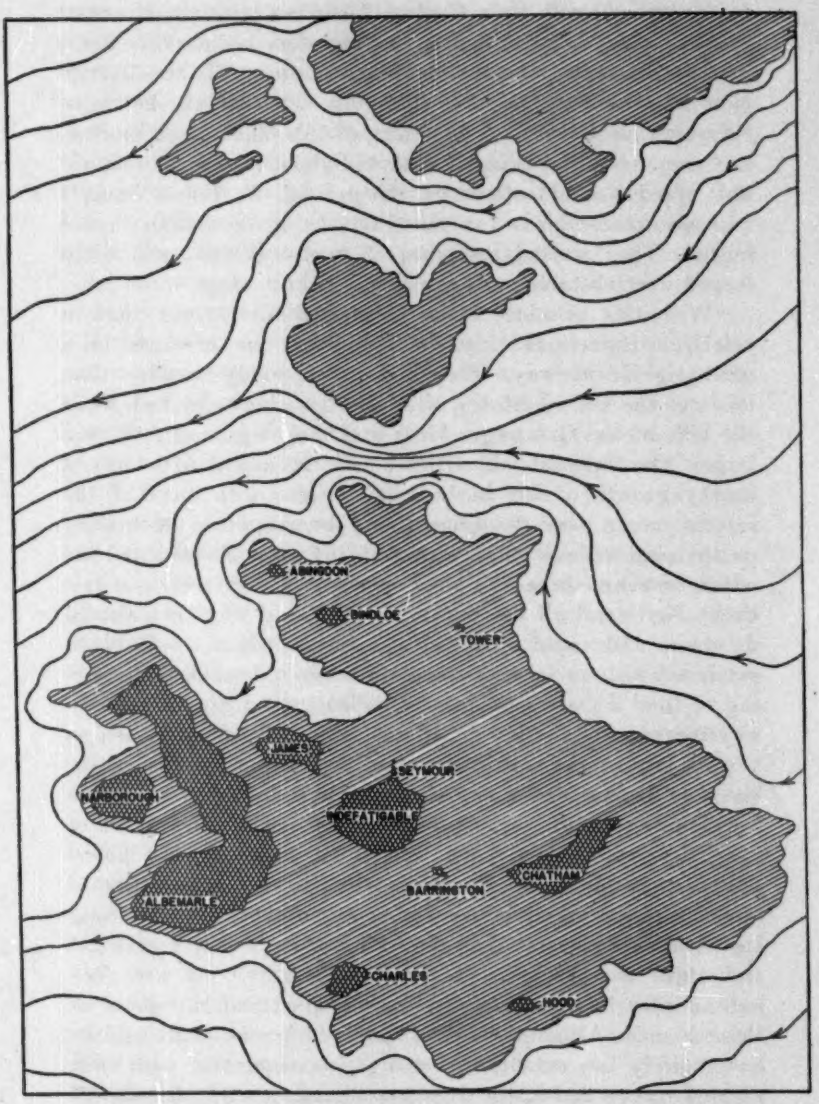

Fig. 2. Detail of hypothetic Galapagos land mass and its assumed relation to terminus of an ancient peninsula. Existing islands are named and shown by cross hatching; hypothetic land shown by diagonal lining.

in comparison with their Central American relatives, the most extreme case in point being the flightless cormorant. Beebe clearly illustrates this point in connection with his description of the Indefatigable mocking birds when he says, "*Nesomimus melanotis* is the name of this black-eared mocker, and one of the first things I observed about it was the remarkable speed it could attain on the ground. As I look back, I remember these birds far more on the ground than in the bushes. They walked and ran, they chased flies, and often leaped over obstacles without opening their wings.

"With this in mind, I was interested to discover that in relative proportions they differed from our mockers in a most significant way. They are considerably smaller than birds of the United States, with shorter wings and tail, while the bills of the Galapagos birds and their legs and feet were larger. On these islands without tall trees, and with only a scanty growth of low bushes and shrubs, with most of the insects on or near the ground and berries often developing on the sand or lava itself, with a steady wind blowing and the ocean so near, there was no inducement for extended or frequent flight and all the reason in the world why they should do much and rapid running. The irregularities of the lava combined with the scanty insect fauna would make the securing of food a matter of greater difficulty and create a necessity for putting the bill to all sorts of unusual uses, such as prying into crevices, splitting small twigs, cracking open the shells of young crabs and mollusks and the eggs of fellow birds, and even pulling the tails off of small lizards—all of which I have seen them doing. So without going into the theory of cause and effect, or natural selection, or which comes first—long legs and terrestial speed, or rapid running and long legs—the fact remains that these birds show a very significant structural change from continental mockers, and are very well adapted to a successful pursuit of food and happiness on these islands. Although from a wholly different angle and to an infinitely less extent, the change is comparable with that which I was to find in the flightless cormorants of Albemarle."

The argument up to this point has centered entirely upon the fauna, but let us not overlook the flora in connection with the proposed continental bridge. Although the Galapagos is more temperate than Central America, one would expect a

large representation from the main plant families found on the mainland to follow the bridge down to the islands. However, nothing even remotely approaching this seems to have happened. As Dr. Stewart points out in his botanical survey, most plant families are represented by more genera on the mainland than species on the islands. With a direct mainland connection how could we account for such a scattered collection of species? Furthermore, how could we explain why whole plant families did not reach the islands at all?

In referring to the thirteen plant families that are represented by more than ten species or varieties, Stewart says, "Of the above thirteen families of vascular plants, the Filices contain the largest number of species; and these, owing to the small size of their spores, would obviously possess greater opportunity of being disseminated over considerable stretches of water than the plants of any other family on the list. Furthermore the small number of endemic species of ferns leads naturally to the supposition that there is a more or less constant introduction of spores from the mainland, thus checking any strong tendency for the species of ferns on the islands to vary greatly from those on the mainland. This supposition is supported by the fact that each collecting expedition brings to light more continental species that were not previously known to occur on the islands."

In discussing animal migrations and the influence of known as well as hypothetical land bridges to explain them, Romer (1933) makes this pertinent statement: "One must not 'erect' a bridge for the convenience of one group of animals without taking into account its effects upon other elements of the fauna: for example, hystricoid rodents with relatives in Africa appear suddenly in South America in the Oligocene. A transatlantic land bridge would afford easy access for the rodents and an easy solution for the problem concerning them. But in both continents there were numerous other animals that one would think equally capable of crossing such a bridge. There is, however, no evidence that they did cross. Land bridges that transmit but one type of animal, and in but one direction, may have existed; but their existence is highly improbable."

Since Cocos Island is the only point of land on the old Costa Rican-Cocos ridge that remains above the sea, one

would normally expect the flora and fauna there to closely resemble that of the Galapagos. However, this is not the case, for studies of the Cocos fauna show that the animal life is very scarce and that the few representatives there show no close relationship to the Galapagos species. Besides the birds and a few imported rats and pigs, a lizard and a snake are the only native vertebrates. The plant life is abundant but also poorly represented. On this point Stewart says, "The flora of the Cocos, like that of the Galapagos Islands, is distinctly that of an oceanic island. The relatively large number of ferns, the much smaller number of species in the remaining families, and the total number of species found on the island lend support to this view. The flora is probably of much more recent origin than is that of the Galapagos Islands. While the island lies nearer to the mainland by nearly three hundred miles, where presumably the various agents that disseminate seeds would work to at least as good advantage as in the Galapagos Islands, yet the number of species represented is probably not more than one-sixth as great. It seems possible that the time that has elapsed since conditions on the island were suitable for the growth of higher vegetation has not been sufficient to stock the island by the slow process of seed dissemination, over considerable areas of water, with as many species as it is capable of supporting. The small number of endemic species of the island might also point to a relatively recent origin of the flora."

Let us continue with Dr. Stewart's idea regarding the recent origin of the flora and point out that there are other evidences that the whole of Cocos Island is of recent origin. In the first place it is composed of volcanic rocks and the manner in which they are weathered and eroded indicates a condition of youth. Fast flowing streams, for example, erode their channels rapidly and usually make concordant junctions with the sea. The Cocos streams, however, run down the steep mountain side and plunge over the cliffs into the sea from hanging valleys. Whether a block fault elevated a portion of the island suddenly, or the ocean waves rapidly cut away softer beds of volcanic ash, cannot be determined without a close examination of the exposed surface, but regardless of the cause, the feature is that of youth. All explorations there report a very thin soil mantle, which is another indica-

tion of short life. If the rate of chemical weathering in Panama can be taken as a criterion, it is probable that an outcrop of Miocene age in that tropical climate would be weathered to a depth of fifty feet, with a thick mantle of residual clay covering all the rock outcrops. Furthermore, the absence of beaches and beach accumulations clearly shows that wave erosion has been in progress for a relatively short geologic time. The absence of beach deposits and shallows also indicates that the island was originally small rather than the remaining core of a large one. In short, there is very strong geologic evidence that Cocos Island is a youthful one and that it was evolved by volcanic action which was possibly followed by block faulting. It is probably of Pleistocene age and possibly raised itself from the old Costa Rican-Cocos ridge millions of years after the old Cocos bridge with its flora and fauna had disappeared beneath the waves. The new volcanic island was then repopulated by the influence of birds, winds, and flotsam and jetsam of the counter equatorial current, which flows toward Panama. This is a very logical reason why Dr. Stewart found the long isolated Galapagos plants to have 40.9% endemic species while only 8.69% of the Cocos flora was endemic.

One cannot assume that the physical conditions associated with the Galapagos Islands today are the same as in the geologic past without encountering situations that are impossible to accept or explain. It is not surprising in these studies, that the different scientists, each concerned with his particular field of study and the interpretation of the past conditions from the evidence of his research, arrived at theories that were highly contradictory. Under present conditions—winds and ocean currents moving constantly from the south and southeast during nine months, and dead calms alternating with changeable winds for the balance of the year; the Panama current now passing far north of the Archipelago; and 900 miles of salt water separating the islands from Panama and Costa Rica—one would be hard pressed to explain how any life other than the forms carried by birds could ever arrive from Central America. On the other hand the idea of a complete land bridge leans too far in the opposite direction and a great body of evidence, as we have already pointed out, denies this as a possibility. How-

ever, the proposed Costa Rican-Cocos bridge extending to within approximately one hundred miles of the ancient Galapagos land, offers a logical solution to some of the most perplexing problems confronting both schools of thought. Under these conditions all the amphibians, for example, would still be killed by salt water before reaching Galapagan shores. The mammals would still be excluded while the reptiles, flightless insects, arachnids, myriapods, plants, and small birds would arrive in varying abundance, but always in a haphazard manner when compared to their relatives on the mainland.

The climate on the old Cocos bridge would have been tropical well down toward the Galapagos, so that some ancient tortoise, perhaps the same ancestor as Panama's land tortoise (*Testudo tabulata*) might, under ideal conditions, reach the Galapagos land mass on a drifting tree trunk in the matter of a few days. In spite of the many enemies of *Testudo tabulata* in the Panama jungle, it sometimes grows to a length of two feet. Its ancient ancestor may or may not have been larger, but regardless of this, in a habitat devoid of enemies, it might well have developed into the present giant tortoise. On the other hand, tortoises were widely distributed in North America during Miocene and Pliocene time, and the ancestor of the Galapagos tortoises may have been a relatively new arrival in Central America and only distantly related to *Testudo tabulata*.

In conclusion, the submerged mountain range still extends from Costa Rica to a point many miles beyond the present Cocos Island, and there seems to be no valid reason why the proposed Costa Rican-Cocos bridge could not have existed during Oligocene and Miocene time; if it did exist during that period, a great body of conflicting, contradicting, and confusing scientific evidence concerning the manner in which the ancient Central American and West Indian flora and fauna reached the Galapagos Islands would suddenly make sense.

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Division of Schools
Canal Zone Junior College
Balboa Heights, C. Z.

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THE DIRECTIONAL CONCENTRATION OF OPTIC AXES IN YULE MARBLE— A COMPARISON OF THE RESULTS OF PETROFABRIC ANALYSIS AND LINEAR THERMAL EXPANSION

JOSEPH L. ROSENHOLTZ AND DUDLEY T. SMITH

ABSTRACT. The coefficients of thermal expansion of 390 grains of calcite in Yule marble were computed from microscopic measurements of their optic axis orientations. Directional percentage concentrations of optic axes, calculated from experimental thermal expansion studies of oriented specimens, compare favorably with the results obtained from microscopic observations. Small dilatational changes in Yule marble are reported at 343°C. and 458°C.

INTRODUCTION

IN their fabric analyses of Yule marble, Knopf (1949) and Turner (1949) measured the optic axis orientations of several hundred grains of calcite in three mutually perpendicular sections (P, Q and R) cut respectively normal to the horizontal N-S and E-W, and to the vertical geographic directions of oriented field specimens (fig. 1). In addition, Turner and Ch'ih (1950) made similar studies of 100 grains of one R section which had been heated to 700°C. It was found that the grain orientations in all sections were such that the optic axes were markedly concentrated in the E-W horizontal direction. According to Dr. Turner's results, which are in general agreement with Dr. Knopf's findings, *52 percent of the optic axes lie at angles ranging from 55° to 90° to the plane of foliation;* the latter has been reported by Dr. Knopf as having an approximately vertical dip and a N 5° E strike.

The purpose of this study was to ascertain whether a good approximation to Turner's results could be obtained by calculation from experimentally determined values of the coefficients of linear thermal expansion, α, of the marble.

CALCULATION OF α

In order to investigate the possibility of a reasonable correlation between fabric analysis and thermal expansion, Professor Turner kindly made available the petrofabric data ob-

tained during his studies of both heated and unheated Yule marble. He also supplied photomicrographs (27x) showing all measured grains for each orientation. Dr. C. S. Ch'ih was kind enough to prepare a camera lucida sketch of the section which had been heated.

The first step in the calculations consists of finding the actual orientation of the *c* axis of each grain in the thin section from the fabric measurements of that grain. This is done by reversing the measured stage rotations and computing the direction cosines, as follows:

$$\cos \alpha = \sin \lambda_1 \cos \lambda_2$$
$$\cos \beta = \cos \lambda_1 \cos \lambda_2$$
$$\cos \gamma = \sin \lambda_2$$

where λ_1 is the horizontal and λ_2 is the vertical rotation recorded in the universal stage data. The directional expansion values are next computed, as explained in the following example. Let us assume that the fabric measurements for a

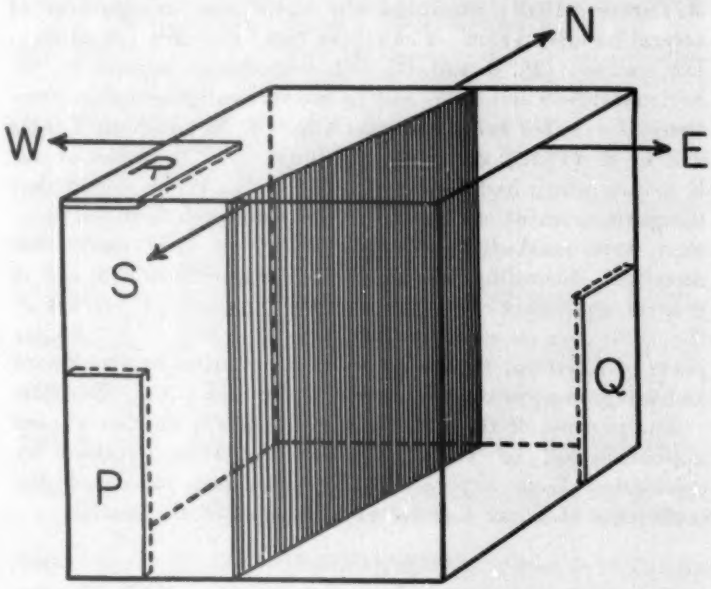

Fig. 1. Diagram showing the orientation of thin sections P, Q and R with respect to the geographic coördinates of a field specimen of Yule marble. The shaded plane is a foliation plane.

particular grain in a section cut perpendicular to geographic vertical is 163°←12° when geographic E-W coincides with the E-W axis of the universal stage before rotations. Here λ_1 is 163° and λ_2 is 12°, from which the formulae above give: $\cos^2\alpha = 0.082$, $\cos^2\beta = 0.874$ and $\cos^2\gamma = 0.043$. For a calcite single crystal Rosenholtz and Smith (1949) obtained the fundamental values of $a_{\parallel} = 23.58 \times 10^{-6}$ and $a_{\perp} = -5.22 \times 10^{-6}$. Since a for calcite is a linear function of the square of the cosine of the angle of inclination to the c axis, the $\cos^2$ values are used to calculate a for the several geographic orientations of the grain in question, and give:

$$\text{N-S} = -2.82 \times 10^{-6} \qquad \text{E-W} = +19.95 \times 10^{-6}$$
$$\text{Vertical} = -4.25 \times 10^{-6}$$

This process was repeated for each of the 390 grains and the averages of the results so obtained are compiled in table 1, with the addition of data from dilatation measurements.

The average volume coefficient for the unheated sections of marble, calculated from fabric data, is thus 13.13×10^{-6}, which is essentially the value obtained by calculation from the

TABLE 1

Directional and Volume Coefficients of Thermal Expansion of Yule Marble Calculated from Measured Optic Axis Orientations, Using $a_{\parallel} = 23.58 \times 10^{-6}$ and $a_{\perp} = -5.22 \times 10^{-6}$ for Calcite.

	Number of grains	N-S x10⁶	E-W x10⁶	Vertical x10⁶	Volume x10⁶ Calculated
Section P, unheated	100	0.82	10.68	1.63	13.13
Section Q, unheated	90	0.14	12.13	1.14	13.41
Section R, unheated	100	-0.11	12.03	0.95	12.87
Average, unheated	290	0.28	11.61	1.24	13.13
Section R, heated to 700°C.	100	0.43	13.78	-0.89	13.32
First cycle, experimentally determined values, 20°-100°C.		4.25	17.75	4.25	26.25
Second cycle, experimentally determined values, 20°-100°C.		-3.75	5.88	-2.62	- 0.49
Calcite single crystal, 20°-100°C.					13.14

experimentally determined linear coefficients of Iceland spar, 13.14 x 10^{-6}. This coincidence makes it clear that, although the location of the *c* axis of some grains may be in error by some few degrees, as Turner (1949) has explained, the results obtained from good fabric measurements of a sufficient number of grains gives a statistical value of α which is as precise as the experimentally determined value. It is to be noted, however, that this procedure does not take into account any condition of internal strain since the expansion coefficients of unstrained calcite are used in the calculations.

The great divergence between the calculated and measured values of α given in table 1 directed attention to the question of the relative size of the grains which were selected for microscopic measurement. Accordingly, the diameters of all grains in one section were measured in mutually perpendicular directions on its 27x numbered photomicrograph. Having previously determined the directional values of α for each grain, it was found that the average of the values of α *x grain diameter* gave results which were practically the same as those given in table 1. Another line of investigation consisted of making traverses across all measured grains at intervals equivalent to an actual spacing of 0.01″ on the marble, and an average was computed. Again the results were essentially the same, indicating that it is possible to assume that the random selection of large and small grains of various orientations gives an average value of α such that the grain size may be disregarded.

INTERPRETATION OF VALUES OF α

The directional values of α for the unheated section R differ somewhat from those of the same orientation which was heated to 700°C., as shown in table 1. Turner and Ch'ih (1950) have reported small differences as a result of their fabric studies of these sections. Perhaps such small differences, difficult to resolve, are sufficient to account for the variation in α. From the point of view of this study, however, the most important result reported by Turner and Ch'ih is that the heating and subsequent cooling have produced no significant change in either mean grain size or orientation.

The calculated coefficient of volume expansion 13.14 x 10^{-6} was obtained from the linear coefficients of a calcite single crystal which showed no evidence of strain. It may be as-

sumed, therefore, that any significant departure from this value, either above or below, represents and is some measure of the internal strain. Rosenholtz and Smith (1950) have shown that pure magnesium and steel display large changes in a, both increasing and decreasing, depending upon the magnitude of the imposed compressive stresses. The calculated volume coefficient obtained from dilatation measurements of the first heating cycle of Yule marble, 26.25×10^{-6}, is thus an indication of an appreciable condition of internal strain. The corresponding value for the second heating cycle, -0.49×10^{-6}, must also be due to internal strain and presumably resulted from the first heating-cooling cycle. Some thermal treatments relieve strain; others induce strain. It is known that the extent of strain relief by thermal methods depends upon such factors as the physical nature of the material, the magnitude and nature of the originally imposed stress, the maximum heating temperature, the duration of the heating, and the cooling program. The problem is further complicated in an anisotropic polycrystalline substance such as marble by the great anisotropy of thermal expansion of calcite. Some of the effects of cyclic heating and anisotropic expansion which have been reported by Boas and Honeycomb (1946, 1947) for some metals may apply equally well to non-metallic materials.

If all initial strain in a pure calcitic marble, such as Yule marble, is relieved by thermal treatment, and if no new strain is introduced by such treatment, it may be expected that the coefficient of volume expansion should approximate the value of unstrained calcite, 13.14×10^{-6}. Accordingly, the authors are now of the opinion that any computations of c axis concentrations should be based upon the coefficients of linear expansion during the first heating in the 20°-100°C. range.

CALCULATION OF OPTIC AXIS CONCENTRATIONS

There are two sets of directional values of a which are now to be used to calculate c axis concentrations, one calculated from fabric data and the other from experimental measurements. The former necessarily assumes no internal strain and depends solely upon the measured position of the c axis of each grain; the latter includes not only the grain orientation but also the indeterminate effect of internal strain. In either

case, two assumptions are necessary. The first, as has been explained, is that the most reliable experimental values of α are those obtained during the first heating from 20° to 100°C. The second assumption is that the *c* axes of the individual calcite grains in the marble are either parallel or perpendicular to the axes of the test specimens; the latter are the directions of measurement of dilatation and correspond with the geographic coördinates of the field specimens. Using the experimentally determined values of α for a single crystal of calcite, $\alpha_{\parallel} = 23.58 \times 10^{-6}$ and $\alpha_{\perp} = -5.22 \times 10^{-6}$, it is possible by simple algebraic calculation to obtain a value of the directional *c* axis concentrations from the values of α obtained from either fabric data or dilatation. For example, using the average α N-S calculated from fabric measurements, 0.28×10^{-6} we obtain:

$$23.58 \times 10^{-6} X + (-5.22 \times 10^{-6})(100-X) = 0.28 \times 10^{-6} \times 100.$$

From this it is found that the *c* axis concentration in the *N-S direction is 19.1%;* the other directional values of α give the *E-W concentration = 58.4% and the vertical concentration = 22.4%*. It is to be noted that sum of these percentages is 99.9%. This is due to the fact that the coefficient of volume expansion is 13.13×10^{-6}, which is the no-strain criterion suggested above for calcite.

The experimental values of α determined during the first cycle will be used in the second example. From these data the following concentrations are first obtained:

N-S = 32.9% E-W = 79.7% Vertical = 32.9%

In this case the calculated coefficient of volume expansion is 26.25×10^{-6}, indicating a condition of strain. Since the computed percentages total 145.5%, the respective percentages are recomputed to 100%, the results being:

N-S = 22.6% *E-W* = 54.8% *Vertical* = 22.6%

It may be concluded from a comparison of the results above with Turner's findings that, for Yule marble, a satisfactory value of the geographical directional concentration of the optic axes can be obtained by simple calculation from the coefficients of linear thermal expansion. Conversely, directional values of α may be computed from fabric data, but the calculations must be performed for each of a reasonably large number of grains and, furthermore, the results will represent a no-strain condition.

DILATATIONAL CHANGES IN YULE MARBLE

In attempting to evaluate the data obtained from the second cycle heating of Yule marble, a thermal point was sought where the coefficient of volume expansion would be numerically equal to that of unstrained calcite, namely, 13.14×10^{-6}. By interpolation this was found to be 458°C., at which temperature the calculated *c* axis concentrations are:

N-S = 18.9% E-W = 60.5% Vertical = 20.5%

These concentrations are in reasonably good agreement with those obtained from both fabric and experimental data. All dilatation records of Yule marble were then re-examined and it was found that all second cycle records showed very small changes in the slope of the dilatation—temperature curve in the vicinity of 340°C. and 460°C., the averages being 343°C. and 458°C. Some of the first cycle records give evidence of these dilatational changes but they are obscured in most cases due to the much larger expansion rate during the first heating. Since neither of these changes has been detected for a calcite single crystal, it is believed that they are related in some manner to the deformational history of the marble. Both changes are indeed small but the one at 343°C. is more pronounced than that at 458°C. Rosenholtz and Smith (1949) previously reported the change at 343°C. as being in the 300°-400°C. range and suggested that it might be due to the initiation of recrystallization. Turner and Ch'ih's (1950) findings make this improbable since no conclusive microscopic evidence of recrystallization was discernible. As a result, it is not possible to suggest an explanation at this time as to the significance of the two changes.

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Rensselaer Polytechnic Institute
Troy, New York

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A NEW BELEMNOID FROM THE TRIASSIC OF NEVADA

ALFRED G. FISCHER

ABSTRACT. A belemnoid from the Norian Gabbs formation of Nevada shows the external characteristics of the genus *Atractites* Boehm but contains a holochoanitic siphuncle composed of invaginated funnels (septal necks?) each of which extends through slightly more than two chambers. The name *Choanoteuthis mulleri* is proposed.

INTRODUCTION

IN the course of his studies on the Triassic of Nevada, Dr. Siemon Muller collected a belemnoid in the Norian Gabbs formation of the Gabbs Valley Range which, on external characters, resembled *Atractites* Boehm. This genus, as Flower (1944) has pointed out, has been used as a catch-all for early Mesozoic belemnoids with straight, axially located conchs[1] and smooth rostra. Thin-sections of the specimen revealed a type of siphuncular structure which differs markedly from any heretofore recorded for cephalopods of any sort, though somewhat resembling that of the holochoanitic nautiloids and of the Jurassic belemnoid *Megateuthis quinquesulcatus* de Blainville. Although the specimen at hand is only a fragment of rostrum and conch from the mid-alveolar region, the character of the siphuncle is so distinctive and of such potential significance to an understanding of belemnoid relationships that it is proposed to make it the basis of a new genus.

PHYLUM MOLLUSCA

CLASS CEPHALOPODA

Subclass Dibranchiata

Order Belemnoidea

Genus *Choanoteuthis*, n.g.

Description.—This genus is established for dibranchiate cephalopods which possess smooth, calcareous rostra of radiating fibers or prisms, slender conchs which are axially located (rather than excentric), fairly long chambers, and straight, slender, ventral siphuncles of holochoanitic structure; the siphuncle is composed of long, invaginated, retrosiphonate funnels, each of which extends through two or more preceding

[1] The term *conch* is here used collectively for the phragmocone, conotheca, and proostracum. It thus includes the entire skeleton except the rostrum.

chambers. These funnels are calcareous and comparatively thick, appearing to be greatly extended septal necks. However, the material at hand is not sufficiently well preserved to permit a definite conclusion as to whether they are septal necks throughout, or whether they are in part composed of thick, calcareous connecting rings of the type encountered among holochoanitic nautiloids (Flower, 1947).

Discussion.—Belemnoids possessing long, straight, axially located phragmocones and smooth, calcareous rostra have in the past been referred to *Atractites* Boehm. As there exists uncertainty about the genotype of *Atractites*, Flower (1944) has urged the transfer of most species from this into a newly established genus, *Ausseites* Flower, based on *Atractites ausseanus* Mojsisovics, and has split off from this group the genus *Metabelemnites* Flower, based on *Atractites philippii* Hyatt and Smith from the Upper Triassic of California.

Choanoteuthis resembles *Ausseites* and differs from *Metabelemnites* in its small angle of expansion, its comparatively long chambers, and in possessing inflated rather than cylindrical siphuncular segments. The microstructure of the siphuncle of *Metabelemnites* is not known. *Choanoteuthis* differs from *Ausseites* in the structure of the siphuncle: the genotype of the latter shows an essentially orthochoanitic development of short septal necks and long, delicate connecting rings which are slightly inflated. *Choanoteuthis* is thus readily differentiated from the other genera of belemnoids characterized by straight, axially located conchs and smooth rostra. Its siphuncular structure appears to be more closely related to (though not identical with) that of *Megateuthis quinquesulcatus* de Blainville from the Jurassic, described by Christensen (1925). In this form, the septum is extended into a funnel (it is not clear whether this is a septal neck, or connecting ring, or both) which extends apicad for a distance of one and one-half

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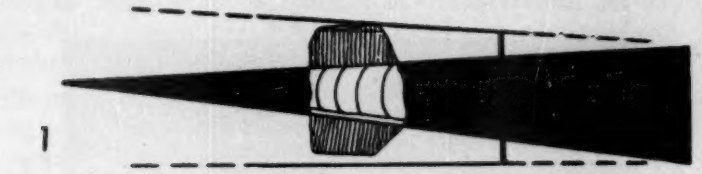
Plate 1. *Choanoteuthis mulleri*, holotype.

Fig. 1. Longitudinal thin-section, shown in relation to the restored alveolar position of the rostrum. (Drawing)

Fig. 2. Transverse thin-section, x 4. A septum is intersected near its junction with the shell wall. The siphuncle is not quite marginal. (Unretouched photograph.)

Fig. 3. Longitudinal thin-section, x 4. In this section the siphuncle is marginal. (Unretouched photograph.)



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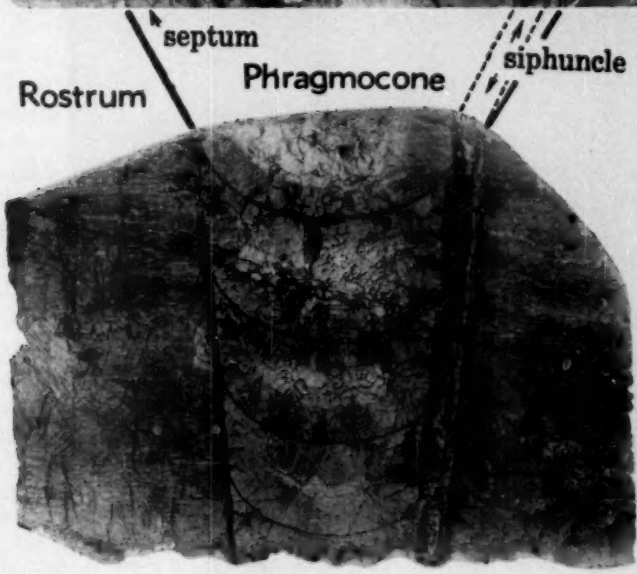

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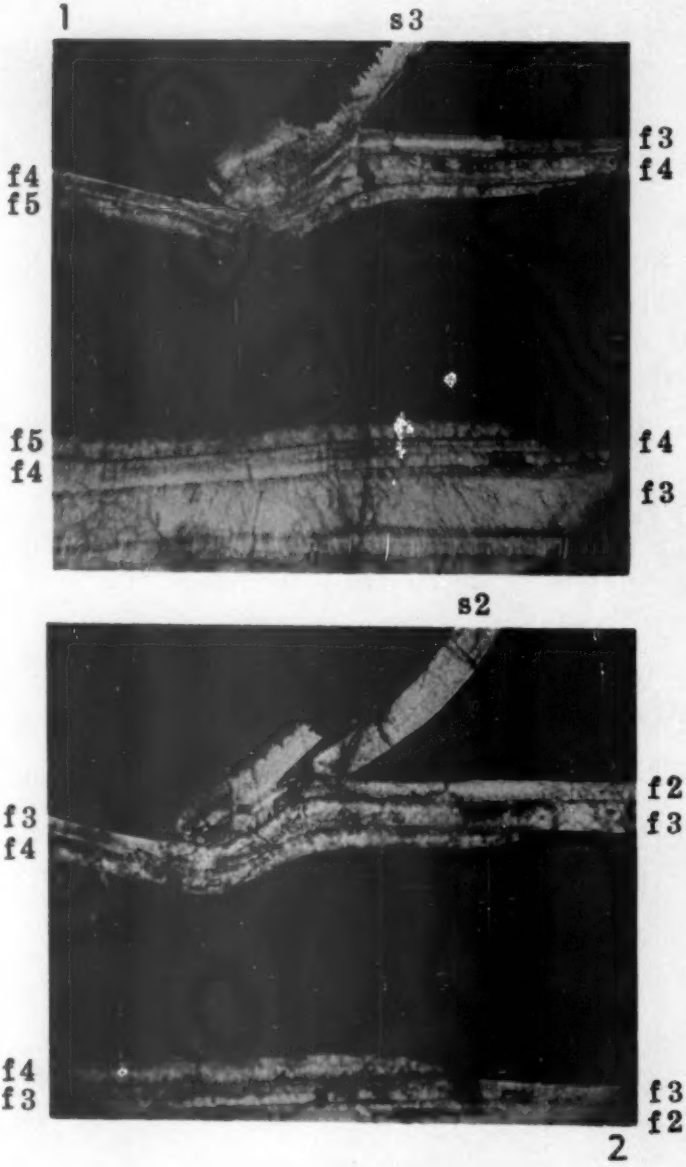
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chambers. *Megateuthis*, in contrast to *Choanoteuthis*, has an excentrically located phragmocone, a large angle of expansion, and short chambers.

Choanoteuthis represents the first record of elaborate, *i.e.* nonorthochoanitic, siphuncular structure among pre-Jurassic belemnoids. Paradoxically, its siphuncle is also the most elaborate one known among belemnoids, regardless of age. The phylogenetic history of belemnoid siphuncles thus appears to parallel to some degree that of the nautiloids, both groups having developed holochoanitic forms at the time of their first great morphologic radiation and their rise to abundance, which in the case of the nautiloids lies in early Ordovician and in the case of belemnoids in Triassic time.

Genotype.—The genotype of *Choanoteuthis* is *C. mulleri* n. sp., from the Norian of Nevada.

Choanoteuthis mulleri n. sp.

Plate 1, figs. 1-3, Plate 2, figs. 1-2, Text fig. 1

The holotype and only specimen is represented by two thin-sections of the mid-alveolar region, one a dorso-ventral longitudinal section, the other transverse.

Rostrum.—The portion of the rostrum at hand (plate 1) shows a roughly circular cross-section with a diameter of 19 mm. in the transverse section (plate 1, fig. 2). The ventrolateral quadrants are slightly flattened. The surface is smooth, devoid of sulci, costae, or vascular furrows. The rostrum appears to thicken slightly apicad. As the adapical and adoral portions of the rostrum are missing, the length, overall shape, and the presence or absence of furrows in these areas remain undetermined. The interior of the rostrum is composed of calcite prisms, considerably coarser than the fibers found in well-preserved Jurassic and Cretaceous belemnite rostra. It is not certain whether these prisms represent the original structure, or whether they have been secondarily (diageneti-

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Plate 2. Siphuncle of *Choanoteuthis mulleri*, holotype, x 62.

Fig. 1. Foramen of the third septum (s3) in longitudinal thin-section. Funnels of septa 5 (f5) and 4 (f4) lap over neck of septum 3; f5 wedges out a little way behind septum 3, leaving f4 and f3 to continue apicad.

Fig. 2. Foramen of the second septum (s2) in longitudinal thin-section. Funnels of septa 3 (f3) and 4 (f4) lap over septum 2; a short way behind septum 2, f4 wedges out, leaving only f3 and f2 to continue apicad.

cally) produced by the reorientation and integration of adjacent fibers. The writer is inclined to favor the second alternative, particularly as the absence of growth lines (*laminae obscurae*) in all but the innermost portions of the rostrum suggests alteration.

Conch.—The longitudinal section of the conch includes three complete chambers in the mid-alveolar region (text fig. 1, plate 1, figs. 1, 3). The angle of divergence is 11.5°. In cross-section (plate 1, fig. 2) the conch appears to be slightly oval, measuring 12.2 mm. dorso-ventrally at a lateral diameter of 11.8 mm. The chambers show the following length-height dimensions (the height of each chamber being measured dorso-ventrally at the suture of the adapically bounding septum) 2.5 : 6.2 mm.; 2.8 : 6.7 mm.; 3.3 : 7.3 mm.; 3.8 or more : 7.9 mm.

The conotheca and septa, presumably originally of aragonite, have become recrystallized to calcite, but despite the attendant loss of microstructure the individual shell layers have largely remained distinct. The conotheca shows two well-defined layers (text fig. 1). The thin *annulus-layer* of Nautilus is either wanting or not recognizable. The septa show no layering. Their areas of adnation are rather broad, as the septa wedge out gradually in orad direction, and are supported on the adapical side by deposits similar to those found in *Nautilus*. The septa are not prolonged along the dorsal wall, but along the venter they extend farther orad than on the dorsum, forming what may be a short mural tongue or a ventral saddle (alternatives which cannot be decided from the thin-sections at hand).

Siphuncle.—The siphuncle lies at or near the ventral margin; in the longitudinal section the material between the conotheca and the lumen of the siphuncle appears to be almost entirely taken up with thick septal matter (mural parts and septal necks), whereas the transverse section (plate 1, fig. 2) shows the siphuncle separated from the conotheca by 0.1 mm. of chamber-filling matrix. In this section the siphuncle is distinctly broader than high. As seen in text figure 1 and plate 2, the siphuncle is constricted at the septal foramina, and expanded in the chambers. Its wall is approximately 0.1 mm. thick, *i.e.* comparable in thickness to septa or conotheca, is calcareous, and consists of two or, just behind each septum,

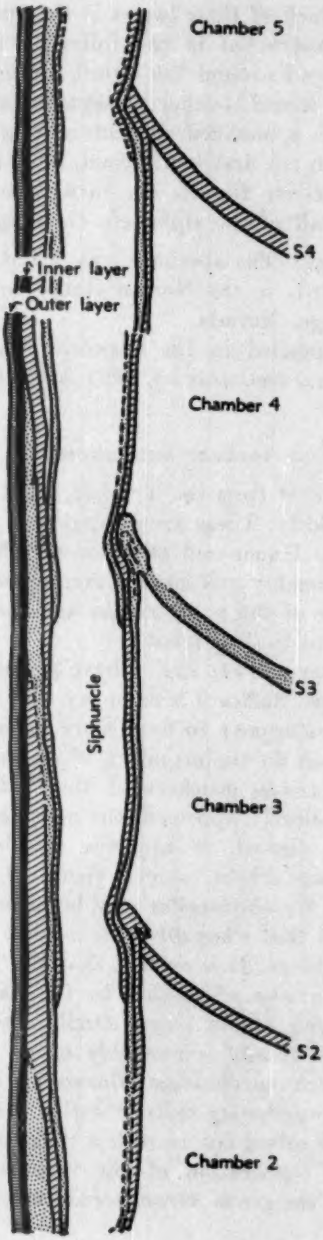

Fig. 1. *Choanoteuthis mulleri*, holotype, x 25. Diagram of siphuncle, prepared from a photographic enlargement of the longitudinal thin-section. The outer and inner layers of the shell wall are succeeded in the interior by the crowded septal funnels on the ventral margin of the siphuncle. Septa and their funnels are alternately cross-hatched and stippled to facilitate tracing.

three layers, (plate 2). Each of these layers is the apicad extension of a septum, constructed in the following manner: Each septum extends apicad around the septal foramen, into an extraordinarily long funnel (either a septal neck or a septal neck combined with a modified connecting ring) which lines the siphuncle through the first and second, into the third preceding chamber. Successive funnels are invaginated, thus producing the multiple wall of the siphuncle (text fig. 1).

Locality and repository.—The specimen was found by Dr. Siemon Muller at Loc. 781, in the Norian Gabbs formation of the Gabbs Valley Range, Nevada.

The specimens are deposited in the Stanford University Collections: the longitudinal section is no. 8027, the transverse section, no. 8028.

RELATIONSHIPS OF TRIASSIC BELEMNOIDS

Of various genera reported from the Triassic, eight appear to have some claim to validity. These are compared in table 1. Of them, only *Aulacoceras* Hauer and *Dictyoconites* Mojsisovics can be said to be reasonably well known; even among these such features as the shape of the proostracum and the details of shell structure remain to be discovered.

Naef (1922) and Flower (1944, 1947) have discussed the classification of these forms. Suffice it here to say that whereas most of the Triassic forms appear to have more strongly developed phragmocones than do the majority of Jurassic and Cretaceous belemnoids, various members of the "*Atractites* group" in other respects closely approach the morphology of the Jurassic belemnites. Indeed, it appears possible that *Atractites* includes, among others, stocks ancestral to the Jurassic Hastitinae, that *Metabelemnites* may be ancestral to the Belemnoteuthinae, and that *Choanoteuthis* may be a forerunner of the Passaloteuthinae. It is evident that the Triassic belemnoids represent a variety of stocks. In the past they have generally been lumped into a single family, the Aulacoceratidae Bernard. This family is probably not a natural unit, but it is felt that much morphologic information must be accumulated before a thoroughgoing reclassification is feasible.

The main problem to be solved before such a reclassification can be successful is the segregation of the various stocks which have been lumped in the genus *Atractites* Guembel. These

TABLE 1
Triassic belemnoid genera

		ROSTRUM			PHRAGMOCONE		SIPHUNCLE	RANGE
		Relative shape	Lateral furrows	Ornamentation	Alignment	Angle of expansion		
	Aulacoceras Hauer	fairly short, blunt	present	costate	straight, axial	5–12°	orthochoanitic	Upper Trias.
	Dictyoconites Mojsisovics	long, slender	"	costate	straight, axial	5–12°	"	Upper Perm.-Upper Trias.
	Actinoconites Stolley	long, slender	"	smooth	straight, axial	5–12°	?	Upper Trias.
"Atractites group"	*Atractites* Guembel	long, slender	absent	"	straight, axial	5–20°	orthochoanitic	Lower Trias.-Lias.
"Atractites group"	*Metabelemnites* Flower	short, blunt	"	"	straight, axial	12° ±	?	Upper Trias.
"Atractites group"	*Choanoteuthis* nov. gen.	?	"	"	straight, axial	11° ±	holochoanitic	Upper Trias.
	Calliconites Gemmelaro		present	"	slightly excentric	large	?	Upper Trias.
	Zugmontites Reis		?	"	curved, excentric		?	Middle Trias.

stocks resemble each other in possessing large, well calcified, straight phragmocones, and smooth rostra devoid of lateral furrows. Flower (1944) recognized the need for separating the various components. He attempted a division based upon the length of the post-alveolar portion of the rostrum, and recognized two groups: most of the species referred to *Atractites*, and typified by *A. ausseanus* Mojsisovics, possess a rostrum which extends far apicad beyond the tip of the phragmocone; *A. philippii* Hyatt and Smith, on the other hand, is characterized by a rostrum best developed in the alveolar region, terminating a short way behind the latter. Flower was not able to determine to which of these groups the type species, *Atractites alpinus* Guembel, belongs. He has therefore proposed that the genus *Atractites* be dropped, and that the majority of its members, characterized by apically extended rostra, be placed in the new genus *Ausseites* Flower (based on *Atractites ausseanus* Mojsisovics); furthermore, he has made *A. philippii* Hyatt and Smith the type species of the new genus *Metabelemnites* Flower, characterized by a rostrum extending only a little beyond the alveole.

There can be no question about the propriety of separating *Atractites philippii* from the forms possessing extended rostra. it is, however, to be regretted that Flower did not supplement Hyatt and Smith's figures (1905) with further illustrations and measurements of *Metabelemnites* in order to clearly illustrate the nature of the rostrum. It is also regrettable that neither illustrations nor measurements have been published for the rostrum of *Ausseites ausseanus*, the type species of the genus with which *Metabelemnites* is contrasted.

The writer feels that the advisability of dismissing the genus *Atractites* has not been adequately demonstrated. It appears highly probable that *Atractites* Guembel and *Ausseites* Flower are synonyms; until further facts have been brought to light, and an effort has been made to check the type specimens, the author will tentatively consider them as such.

Flower's subdivision of the Atractites group represents a step in the right direction; however, studies will have to be extended beyond surficial features. The discovery of the above-described *Choanoteuthis* points to diversity of siphonal structures among these forms, and Christensen's discoveries of cameral deposits in Jurassic belemnoids point to another

feature of potential usefulness in classification. Much light has been shed on the relationships of Jurassic and Cretaceous belemnites by studies of the ontogeny of the rostrum, as seen in section; this method also remains to be applied to the *Atractites*-like forms of the Trias and Lias.

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Hyatt, A., and Smith, J. P., 1905. The Triassic cephalopod genera of America: U. S. Geol. Survey Prof. Paper 40.

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University of Kansas
Lawrence, Kansas

REVIEWS

Geografía General de México (*Geografía Física*), *Vols. I and II;* by JORGE L. TAMAYO. Pp. 1208; 22 plates, 587 figs. *Atlas,* 19 maps (18 x 26 inches), 34 small maps (6 x 8 inches), 10 charts. (In Spanish) Mexico, 1949 (Talleres Gráficos de la Nación, 75 pesos, $8.65).—This is a treatise on the physical geography of Mexico. So complete is its scope that it has definite value in the geological fields of geomorphology, volcanology, and shoreline studies far beyond that indicated by its title. Geographers and geologists, as well as cartographers, meteorologists, physicists, foresters, and economists will profit from the descriptions, colorful maps, and charts. Many of the data presented in both volumes and Atlas are not original, but taken from authoritative sources and specialists, to which credit is given freely. It is a collection of a large amount of information, and hence a valuable reference for any scientist.

There are 406 photographs (109 of which are aerial photographs), 115 text maps, 22 plates (black and white), and 66 sketches in the two volumes. Several photographs are very poorly reproduced. The two volumes are paper bound, whereas the Atlas, is loose-leaf bound in a heavy case with three binding posts for ease in removal of the maps, which are tipped in. References as footnotes in the volumes appear reduced to a minimum.

Volume I (628 pages) contains 16 of the 25 chapters. Chapter 3 on Cartography presents a history of Mexican cartography, including page size reproductions and five 13 x 18 inch plate reproductions of old maps. The chapter on Geology is elementary, and the Geological Evolution of Mexico is a generalized scant summary of the historical geology (5 paleogeographic maps). The reader would do better to read Garfías and Chapin's *Geología de México* (Editorial Jus, Mexico, 1949) for a complete summary of Mexican geology. Short chapters on Gravimetry and Geodesy are followed by a well-authenticated and illustrated (74 photographs) chapter on Volcanism.

Chapters on Seismology, Terrestrial Magnetism, and Terrestrial Electricity are followed by four long chapters describing the natural landscape of Mexico: Geomorphogeny, Geomorphography, Shorelines, and Islands. The author has adhered to Davis' original division of geomorphology: the origin of land forms and the description of land forms, which is surprising to find these days. The geomorphogeny of Mexico is subdivided according to the geomorphic units of von Engeln (*Geomorphology,* New York, 1942, pp. 60-69). Each geomorphic unit is carefully related to examples found in Mexico. The geomorphography is separately described (Chapter 14), but based upon the familiar orogenic units into which Mexico is partitioned. This separation into morphogeny and morphography may be of interest to the sincere student of the science, but will be

found superfluous to the casual reader. The chapters on Shorelines and on Islands are embellished with 25 maps of harbors and islands, 21 sketches of shorelines as viewed from the sea, and 30 aerial photographs.

Volume II begins with Climatology, with 34 text maps portraying the usual facets of the subject. Under the title of Hydrology the geology of streams is analyzed, and a brief chapter on Potamology and Limnology includes a table of 162 river drainage basins—all of which are examined in the next three chapters: The Atlantic Watershed, The Pacific Watershed, and Interior Drainage. These are beautifully decorated with 20 maps and 209 photographs. A chapter on Physical Oceanography reports briefly on submarine topography off the Mexican coastlines. The last two on Edaphology and Soil Conservation bring the reader up to date on one of the most vexatious current problems facing Mexico today.

In the Atlas a transparent map of political divisions can be superimposed over the other maps, on which for clarity, the names of political divisions are omitted. All igneous rocks on the Geology map are shown as intrusive, extrusive, or pyroclastic. On a map of this scale, greater subdivision according to age or type perhaps was not feasible. Sedimentary rocks are differentiated according to age. Two blank areas in Baja California, one large blank area in Sierra Madre de Oaxaca, and another on the southeast border of Campeche are reminders of geologic work to be done. The generalized contours on much of the Isohyetal map probably indicate meager data from many parts of the country. Hydrometric stations on the River Drainage map are numbered, with an explanation on the reverse side. All important streams on this map are labelled in fine but legible printing. Large blank areas of mountainous country on the Soil map indicate complex soil on greater than 25 degree slopes, of podsolic and "cafe forestales" nature. Sites on the Archeological map are identified by red checks with accompanying numbers; all are located by state and name (ceramic localities, construction remains, and building ruins included). The Population map shows intensity in eight colored symbols by state, as well as by dots for every 2,000 inhabitants. Seven zones of vegetation are depicted on the Vegetation map. Location of the mines of 25 different minerals is shown, with accompanying charts of mineral production during 1938-1942, silver production since 1521, gold production, and total mineral production since 1929. Forty-four small maps (cartograms) and charts exhibit Distribution of Property, and Silviculture; Fishing, Cattle, and Aviculture; Agriculture and Principal Cultivation; Petroleum, Sugar, and Electricity; Commerce and Finance. The information displayed on most of the large maps is carried as far as practical into United

States and Guatemala. This allows correlation with these adjoining countries, a desirable practice.

The Atlas, handsomely arranged and colored, is well organized and alone worth the price of the set. This work of Tamayo constitutes a valuable contribution for all geographers and geologists alike. It is a step forward in our understanding of Mexico.

SIDNEY E. WHITE

Geología de México; by VALENTIN R. GARFIAS and THEODORE C. CHAPIN. Pp. 202; 6 figs.; 2 tables. (In Spanish). Mexico, 1949. (Talleres de la Editorial Jus, S. A., Mejía 19, México, D. F., Paper-bound, 30 pesos, $3.46).—This book is a copiously documented summary of our current geologic knowledge of Mexico. The principal physiographic divisions of the country, neatly rearranged by Garfias and Chapin, determine the organization of their book. Instead of the customary division according to structural units, the position of the mountain ranges and coastal plains, so dependent upon the underlying rocks and their geologic history, are the controlling instruments. The nine chapters, therefore, besides the Introduction, tell us about the Mesa del Norte, the Mesa Central, Sierra Madre Oriental, Sierra Madre Occidental, Sierra de los Volcanes, Sierra de Chiapas, Planicie Costera del Golfo, Planicie Costera del Pacífico, and Sierra de la Baja California.

Each chapter is a geologic compendium with many quotations from and references to the writings of Mexican and North American geologists. Topography, drainage, stratigraphy, structure, and historical geology each in turn are examined. Geologic eras are chronicled and events of each epoch are analyzed if the surface area of the rocks involved and our information about them warrants.

The bibliography of 639 publications, arranged alphabetically by author, in the opinion of some is the valuable contribution of the book. The figures are black-and-white maps and sections at the back of the text. The geologic map of Mexico, 15x19 inches, assigns the rocks to six categories: intrusive igneous, volcanic, Premesozoic, Mesozoic, Tertiary sedimentary, and Quaternary sedimentary. The authors are not afraid to indicate on their map the geology of areas of which others are still uncertain.

As a reference to which geologists may turn for an account of any portion of Mexico and a lengthy list of references, there is none better.

SIDNEY E. WHITE

Die Lebensweise der Dinosaurier; by MARTIN WILFARTH. Pp. 95; 68 figs., 3 plates. Stuttgart, 1949 (E. Schweizerbart'sche Verlagsbuchhandlung, D.M. 12.—).—The straightforward title of this book conceals an amazing attempt to interpret the fossil remains of dinosaurs in terms of a fantastic hypothesis of "great tides" which the author categorically maintains were a dominant factor of the environment during the Mesozoic Era. Rejecting strict uniformitarianism he assumes that in Early Triassic times the moon was closer to the earth than at present, causing tides of about 30 meters height and of several months period. These tides decreased to about three meters in height and to a five-day period by the end of the Cretaceous. The book is devoted to discussion of adaptations of the dinosaurs to the amphibious life which these conditions required.

Some of the interpretations of dinosaurian structures which Dr. Wilfarth advances are startlingly ingenious. His suggestion that the enlarged nasal openings of sauropods were adaptations to breathing in rough water deserves critical analysis, for these animals are considered by many students as amphibious or largely aquatic. Bipedal dinosaurs of the Triassic and Jurassic are interpreted as "Atemspringer," creatures which leaped from the bottom of the tidal flats to the surface of the water in order to breathe! The peculiar long plates which adorn the back of *Stegosaurus* were baffles which deflected the strong tidal currents in such a way as to hold the animal firmly on the bottom.

Most remarkable is Wilfarth's rejection of the currently accepted interpretation of sauropods as herbivorous. Arguing that herbivores always have grinding teeth, like horses or ornithopod dinosaurs, he maintains that the blunt, blade-like teeth of camarosaurs as well as the plucking teeth of *Diplodocus* are unfitted for plant food. But living herbivorous turtles and lizards do not grind up their leafy foods, and there is no valid reason to suppose that the sauropods, whose abdominal bulk suggests herbivorous diet, could not have digested whole leaves. Wilfarth, however, maintains that these teeth served for plucking small invertebrates from the bottom of the sea.

After briefly reviewing the current hypotheses of causes for the extinction of the dinosaurs and other reptiles and invertebrates at the close of the Cretaceous, succinctly pointing out the weaknesses of each, he announces the simple cause for this extinction—with the beginning of the Tertiary the great tides disappeared, and with them the inhabitants of the great tidal lands!

Space is lacking for the detailed criticism of this work for which the author asks in his preface. His treatment is unscientific in that he repeatedly fails to mention evidence conflicting with his hypo-

thesis. For the most part, the unusual functions which Wilfarth suggests are not compellingly indicated by the preserved remains of dinosaurs, even though some are conceivable. Naively Lamarckian explanations of the elongation of the neck and limbs in dinosaurs, and or the origin of the predentary bone have no place in a modern scientific treatise.

This interpretation of the dinosaurs cannot be taken seriously, nor do these orders support the hypothesis of earth history in which Wilfarth sets them. Fortunately this book has not received the wide publicity which has been given to Velikovsky's "Worlds in Collision," with which it is comparable in numbers of inaccurate statements and improbable interpretations. J. T. GREGORY

An Introduction to Luminescence of Solids; by HUMBOLT W. LEVERENZ. Pp. xv, 569; 143 figs. New York and London, 1950 (John Wiley & Sons, Inc.; Chapman & Hall, Ltd. $12.00).—Mr. Leverenz has written a well balanced, logically developed and reasonably self-contained introduction to a complex subject. In the opening section there is a brief resumé of the accepted concepts regarding elementary particles, atoms, molecules, gases and liquids. There follows a discussion of the solid state, with an emphasis on the ideas which are pertinent to the development of the theories of phosphor behavior.

In the next three chapters, which comprise the greater portion of the book, there is a detailed description of phosphor synthesis, and a thorough discussion of the constitution of the phosphors and their energy levels.

Provided with this background of solids theory, the reader can follow the author's critical analysis of the experimental behavior of phosphors (spectral characteristics, decay laws, efficiencies, quenching, stimulation, etc.). Decisive experiments are discussed objectively in the light of the theory. A summarized account of the properties of phosphors is then presented, followed by a comprehensive discussion of the uses of luminescent materials.

A tremendous amount of data has been incorporated in the text in the form of graphs, charts and tables. Many other notable features such as an interesting appendix, a glossary of terms, a list of references and a complete set of indexes (formula, name and subject) round out this altogether workmanlike book. P. A. LYONS

PUBLICATIONS RECENTLY RECEIVED

Das Polarisationsmikroskop; by C. Burri. Basel, 1950 (Verlag Birkhäuser, paper cover 28.80 Swiss francs, cloth bound 32.80).

Practical Invertebrate Anatomy; by W. S. Bullough. New York, 1950 (The Macmillan Company, $4.50).

Uaxactun, Guatemala: Excavations of 1931-1937; by A. Ledyard Smith. Carnegie Institution of Washington Publication 588. Washington, 1950 (Carnegie Institution, paper cover $9.00, cloth bound $9.75).

Geological Survey Water-Supply Papers, as follows: 968-D Ground-water Exploration in the Natchitoches Area Louisiana—$ .25; 1078 Ground-water Supplies of the Ypsilanti Area Michigan—$ .50; 1079-A, Ground-water Resources of Liberty County Texas—$ .40; 1079-B, Ground-water Resources of Gregg County, Texas—$ .25; 1083, Surface Water Supply of the United States 1947, Part 3, Ohio River Basin—$1.75; 1084, Part 4, St. Lawrence River Basin—$ .60; 1088, Part 8, Western Gulf of Mexico Basins—$ .65; 1091, Part II, Pacific Slope Basins in California—$1.25; 1099, Water Levels and Artesian Pressure in Observation Wells in the United States in 1947, Part 4, South-central States—$ .45; 1103, Use of Water by Bottom-Land Vegetation in Lower Safford Valley Arizona—$1.25; 1105, Hydrology of Massachusetts, Part 1, Summary of Stream Flow and Precipitation Records—$1.00,—Washington, 1950.

Geological Survey Bulletins, as follows: 948-E, Preliminary Report on Corundum Deposits in the Buck Creek Peridotite, Clay County, North Carolina—$ .60; 955-C, Phosphate Deposits of the Deer Creek-wells Canyon Area, Caribou County, Idaho—$ .45; 966-D, Geophysical Abstracts 139, October-December 1949—$ .25; 68 Bibliography of North American Geology 1948—$ .60,—Washington, 1949, 1950.

ERRATUM

In a recent paper on Pleistocene climate in New Mexico (Am. Jour. Sci., vol. 249, pp. 152-168), the writer mistakenly stated (p. 167) that Dr. Ernst Antevs believes that Lake Estancia existed at a time when temperature was greater than at present. To correct my statement, Antevs' views on this matter are presented in the following excerpt from his appendix to Wormington, H. M., *Ancient Man in North America*, Denver Museum of Natural History, Popular Series No. 4, 1949, p. 189: "The lake (pluvial Lake Estancia) therefore may have attained its largest expanse first when the Azores high pressure area, which was displaced southward during the glacial age, again moved sufficiently far north in summer to send masses of moist tropical air in over New Mexico and Texas, as it is doing at present. Since the lake would have been greatly favored if the evaporation had been smaller, the ideal conditions may have prevailed when the summer temperature was somewhat lower than at present."

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